THE UNIVERSITY OF ALBERTA

URBAN AIR POLLUTION AND SPATIAL DISTRIBUTION OF TEMPERATURE

by

© DJURFORS, SVEN GUNNAR

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL, 1969

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled " Urban Air Pollution and Spatial Distribution of Temperature", in partial fulfilment of the requirements for the degree of Master of Science..

ABSTRACT

In 1967 and 1968 instrumented towers and thermograph networks were placed in operation in the cities of Edmonton and Calgary, Alberta, for continuous measurement of winds and temperatures in prairie city environments. In addition, a mobile unit was provided for horizontal temperature traverses and tape samplers yielded continuous horizontal of smoke concentrations at several points in each city. Some of the data from these sources are used in analyses of the structure of the urban heat island in Edmonton and Calgary and in analyses of the contribution of selected meteorological parameters to the total variability of daily smoke concentrations in Edmonton.

A statistical model is derived for the prediction of mean daily output of smoke in Edmonton. However, the derived discriminant functions fail and this failure is attributed to either (a) improper choice of predictors or, (b) poor estimates of the predictand. Seasonal temperature variations do not account for a significant portion of the variation in smoke output. A possible explanation for this is that space heating, which is temperature dependent, is not a major source of smoke, due to the use of natural gas.

Using wind speed, horizontal temperature differences, and vertical temperature differences, a linear multiple regression equation is derived for the prediction of mean daily smoke concentrations in the city of Edmonton. The equation explains about 40% of the total variation in smoke concentration, and shows considerable stability in a test on independent data.

A significant change in temperature is found as one approaches the center of the city from the outskirts. This difference is attributed to differences in heat-storage capacity, differences between incoming and outgoing radiation due to pollution, and the excess heat due to human activities in the city. The urban heat island is divided into at least two parts by the valley of the North Saskatchewan River.

Analysis of the vertical temperature distribution in Edmonton reveals that near-adiabatic conditions prevail during the daylight hours in the summer; and isothermal, or a weak positive or negative lapse prevails throughout the rest of the year. Temperature inversions of moderate strengths occur throughout the year at night and in the early morning hours.

Analysis of the vertical temperature structure in Calgary shows that adiabatic to superadiabatic conditions prevailed during the daylight hours in March, 1968, through September, 1968. Moderate to strong inversions occur throughout these months at night and in the early morning hours.

When results from other sites are studied, it is evident that the Edmonton Tower, more so than the Calgary Tower, represents a typical city environment possibly because of the peripheral location of the latter.

ACKNOWLEDGEMENTS

I take this opportunity to express my gratitude to Mr. J.J. Kinisky of Geoscience Research Associates, Limited for granting me a Research Assistantship which has given me the opportunity to pursue advanced studies in the field of Meteorology. In particular I would like to thank my supervisor Dr. K.D. Hage for his constant interest, and for his constructive criticism which was essential for the completion of this thesis.

TABLE OF CONTENTS

CHAPTER		Page
II	PREDICTION OF SMOKE IN EDMONTON	18
	General	18
	Prediction of Smoke Emission Rates (Q)...........	18
	Prediction of Absolute Smoke Concentrations (χ)..	32
III	THE HORIZONTAL AND VERTICAL TEMPERATURE DISTRIBUTION IN EDMONTON AND CALGARY.............	39
	Introduction	39
	Thermograph Data	40
	Conclusion	46
	Temperature Traverses	46
	Vertical Temperature Structure	52
	Comparison with Data from Other Sites	63
IV	CONCLUSIONS	68
BIBLIOGRAPHY	....	71
APPENDIX I	....	
APPENDIX II	....	
APPENDIX III	....	
APPENDIX IVa	....	
APPENDIX IVb	....	

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Pollution History

The quality of the atmosphere on which existing terrestial forms of life are dependent has been recognized as important only during the past few decades. It can be supposed, however, that smoke from volcanoes, forest fires, and domestic heating and cooking arrangements were locally troublesome to our human ancestors. But it is very unlikely that such circumstances were more than incidents, until family units began to live in communities; only then could man produce waste enough to affect the neighborhood. Not much is known from the Medieval period, but from accumulated knowledge of domestic heating practices and limited industrial activities one can draw the conclusion that air pollution was not a serious problem in the villages and towns of the time. The problem of pollution was first recognized following the replacement of wood by coal as the prime source of energy. Various limitations and prohibitions to the use of coal were proclaimed officially and there are even records on punishment of offenders. Until the early part of the twentieth century coal smoke was the major contributor to air pollution and even now coal is still used extensively in many industrialized areas of the world. The use of petroleum products in the forms of gasoline and oil has been enormously accelerated, due to the internal combustion engine. The combustion of oil and gas has diminished the coal smoke nuisance but has instead produced "new" kinds of air pollution. One well-known example is the "Los Angeles smog". This results from the exposure to sunlight of products of petroleum

mixed with oxides of nitrogen. Although most of the pollutants related to petroleum processing and use have toxic and irritative properties of low order, their photochemical reaction products even at very low concentrations may affect life. A new phase of the air pollution problem will arise with the introduction of energy sources such as nuclear power and solar energy. No one knows yet for certain how and to what extent the radioactive by-products of nuclear power will affect the biological environment.

The effects of air pollution can be manifold. It is well known that air pollution will reduce visibility due to the scattering of light from the surfaces of the airborne particles. The degree of reduction is related to the optical airmass, particle size and the density of the medium. The visibility is so poor at times in many industrialized cities that transport and other municipal activities have to be curtailed. Material damage is another widespread effect of air pollution, the value of which has been estimated to billions of dollars annually in the United States alone[1]. A number of plants and crops are very sensitive to certain pollutants and if good air quality is not provided for, this can result, for example, in decreased size and yield of fruits and destruction of flowers. Under extreme conditions the air can become polluted to the extent that it is deadly. Typical examples from the 1940's and 1950's are London, Donora and Meuse Valley. Long, continued exposure to light or moderate concentrations of pollutants

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[1] R.E. Munn, "The Interpretation of Air Pollution Data, with Examples from Vancouver", Canada, Dept. of Transport., Met. Branch, Technical Circular Series, Cir-3454, Tec-351, 1961, p. 1.

may have physiological effects although direct proof is difficult to establish. The many cases of chronic bronchitis in British cities and irritated eyes in Los Angeles seem to be closely associated with air pollution. Although awareness of the problem of city air pollution is increasing it is viewed largely as a problem of the future. Only a few large cities are now using the supply of clean air faster than nature can restore it. Such overuse is likely to occur with increasing frequency as populations increase and migration to urban areas continues.

<u>Diffusion Theory</u>

Serious studies on turbulence and associated diffusion processes started with the simple experiments on the flow of water in long straight pipes described by O. Reynolds as early as 1883[2]. According to Reynolds, turbulent flow could be modelled as a simple mean motion on which was superimposed a complicated eddy motion of an oscillatory character. In his experiments he managed to show that the motion became turbulent when the so-called Reynolds number exceeded certain critical values. Much of the early work on atmospheric turbulence was based on theory that was reminiscent of the theory of viscosity developed in the kinetic theory of gases. Like molecules the eddies transfer momentum from one layer to another by breaking away from the main stream in a region of high velocity, conserving some or all of its momentum until it mixes again with the mean motion in a region of lower velocity. Such momentum transfer would show up as an increase in velocity at the new level and

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[2] O.G. Sutton, <u>Micrometeorology, A Study of Physical Processes in the lowest Layers of the Earth's Atmosphere</u>, McGraw-Hill, New York, 1953, p. 56.

would have the effect of eliminating large velocity differences. This theory was further developed by Wilhelm Schmidt who introduced the coefficient of viscosity which he called "Austausch Koeffizient" ("exchange coefficient")[3]. The analogy between molecular and eddy motion was further extended by Ludwig Prandtl in 1925, who brought in the mixing-length hypothesis by introducing a quantity l which is a unique length characterizing the local intensity of turbulent mixing at any level and which is a function of position[4]. Though much fruitful work has been done using the preceding hypothesis it became evident through recent experimental work that the mixing-length theory had serious defects. In many turbulent exchange problems it has been abandoned in favor of the so-called statistical theories. This new theory was first suggested by G.I. Taylor[5] (1921) in a paper on the problem of diffusion written in a journal devoted mainly to pure mathematics. The theory depends largely upon the concept of correlation in statistics, which is an attempt to measure closeness of relationship numerically. In his work from 1921 Taylor studied the extension of the random walk problem in which there is a variable correlation between the motion of a particle at one time and at some instant later. His famous correlation equation is now the starting point in many fluid mechanics problems. Further advances in the field of turbulence were

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[3]Ibid., p. 68.

[4]Ibid., p. 72.

[5]G.I. Taylor, Proceedings of the London Mathematical Society, Ser. 2, Vol. XX, 1921, p. 196-212.

made with the introduction of Monin-Obukhov's similarity theory in 1954[6]. This theory states that there exist near the ground a velocity U*, a length L and a temperature T* that are essentially invariant with height. When temperature, wind, and height, are expressed nondimensionally as functions of these quantities, a series of nondimensional equations results that is of very general validity in the surface boundary layer. One of the problems of the similarity theory is to relate various dimensionless variables to the dimensionless height ratio z/L where L is the above mentioned length (scaling length).

As the theory was not fully tested by Monin and Obukhov in the field, Taylor (1960) examined the similarity theory using data from work done by Rider (1954) and Swinbank (1955) and concluded that, except in strong lapse conditions where some doubt remained, the similarity theory of Monin and Obukhov applied[7].

A remaining difficulty is the question of relative size of the eddy conductivity K_h and the eddy viscosity K_m which is important in the determination of the scaling length L. Evidence and arguments have occasionally been put forth indicating that the ratio K_h/K_m varies with stability (Swinbank 1955)[8]. However, other investigators

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[6] J.L. Lumley and H.A. Panofsky, The Structure of Atmospheric Turbulence, John Wiley & Sons, New York, 1964, p. 99-102.

[7] R.J. Taylor, "Similarity theory in the relation between fluxes and gradients in the lower atmosphere". Royal Met. Soc., Quarterly Journal, Vol. 89, 1960, p. 67-78.

[8] G.E. McVehil, "Wind and temperature profiles near the ground in stable stratification". Royal Met. Soc., Quarterly Journal, Vol. 90, 1964, p. 136-146.

have failed to detect any systematic variation in the ratio and the question has remained a controversial one.

Air Pollution Measurements in Edmonton

The air pollution problem in Edmonton is not yet severe but due to certain climatic factors has a high potential. A. Daniels in 1964 studied the problem emphasizing the heat island and its relation to atmospheric dispersion[9]. In his study he concluded that there was a significant increase in temperature over the city's built-up areas and at the borders of the central business district. Over the residential areas he found a slow increase towards the city center. Calculations of smoke concentrations based on a modified Sutton's diffusion equation supported his assumption that the pollutants were uniformly distributed vertically throughout the heat island. The maximum mixing height, computed for eight winter months, showed a definite variation with wind direction, being highest with northerly winds, lowest with southerly winds. This, together with the fact that southerly winds were predominant during the actual months of his investigation, convinced him that any plan to develop polluting industries to the south of the downtown area should be ruled out.

In the same year the Department of Health, Government of Alberta, started to take air quality measurements. There are now six A.I.S.I. samplers operating on two hour cycles at various locations in the city. The pollution data have been correlated with wind direction and wind speed and a summary of the results has been published on a yearly basis.

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[9] A. Daniels, The Urban Heat Island and Air Pollution, Unpublished M.Sc. Thesis, University of Alberta, Edmonton, 1964.

The most favorable meteorological condition for the accumulation of pollutants over an isolated urban area would be a combination of persistent light winds and persistent weak vertical mixing. Two parameters - mixing depth and mean wind speed through the entire air volume - have been proposed as basic indicators for the development of an urban pollution potential climatology in the United States[10]. Extensive wind profile measurements and some vertical mixing data are now available for many rural areas, particularly in the United States. Less well known, however, are the effects that cities may have on mean winds and on the intensity and depth of vertical mixing. Diurnal changes in wind speed at low altitudes can be used as a relative measure of the intensity of vertical mixing of momentum because of the normal increase of wind speed with height. An increase in wind speeds at low altitudes and a drop of speeds at higher altitudes results in an intensification of the vertical mixing. An investigation done by Geoscience Research Associates[11] in 1967-68 for the city of Edmonton showed that while the average wind speeds at 10meters were relatively strong (8 to 11 m.p.h. in all months), periods of persistent light winds of a few days duration were not uncommon, particularly in winter. Such periods were less frequent in summer because of intense vertical mixing that results in a pronounced daytime wind speed maximum. Further-

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[10]Report of Geoscience Research Associates Limited to the Department of Health, Government of Alberta, Investigation into pollution in Calgary and Edmonton, April 1, 1967, through March 31, 1968.

[11]Ibid.

more, surface and upper-level winds in Edmonton provided some evidence of urban enhancement of vertical mixing in midday hours in winter and at all hours in summer.

Typical weather situations in which the soiling index would reach relatively high levels in the city are mainly of two kinds:

a. Quasistationary high pressure systems centered close to the city, associated with low winds and downward air movements (subsidence).

b. Trapping of air under a quasistationary front with warm air aloft preventing vertical air movement.

The Purpose of this Study

The two main purposes of this study are to investigate:

(1) The possibility of predicting mean daily smoke concentrations in the city of Edmonton;

(2) The horizontal and vertical temperature distribution over Edmonton, and the vertical temperature distribution over Calgary.

Method of Study

Two different techniques were used in an attempt to predict air pollution in the city of Edmonton. To arrive at useful estimates of the mean daily smoke output in the city, a multiple discriminant analysis relating smoke output with some meteorological parameters was applied to the pollution data obtained from the six smoke samplers. Using regression analysis the author then derived and tested a statistical model for the variation of the mean daily smoke concentration in the city.

In order to find significant features of the horizontal temperature distribution over Edmonton a set of six thermographs were placed

in two concentric circles within the city. The data thus obtained were then analyzed by statistical methods. A few temperature traverses were undertaken to provide more detailed data on selected days. A temperature traverse is a series of temperature measurements taken along a pre-determined route. In an attempt to find significant features of the vertical temperature distribution in the cities of Edmonton and Calgary thermometers at different altitudes were mounted on towers. The data were analyzed statistically and the results were compared with results from other sites.

CHAPTER I

INSTRUMENTATION

General

This chapter describes the various instruments used in the author's investigation. As data are being collected from both Edmonton and Calgary, the instruments from both sites are described. However the analysis will be focused on the Edmonton data.

The CN Tower and Calgary Tower Instruments

The vertical temperature structure in Edmonton is measured by electrical resistance thermometers[1]. The system consists of a balanced bridge, recorder and a sensing element, functioning as follows:

The Circuit.

The measuring element forms one leg of the bridge. When the resistance of the measuring element changes, current flows in the bridge and a voltage unbalance is created in the circuit. This voltage is sufficiently amplified to operate a balancing motor. The balancing motor adjusts the sliding contact on a slidewire to restore electrical balance in the bridge circuit and simultaneously moves the pen to record on the chart the variable being measured. The balancing action starts with the slightest change in the resistance and so the measuring procedure is practically instantaneous.

Sensing Element.

The system is equipped with a resistance thermometer bulb, a temperature sensing element which changes resistance with variations

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[1]Bristol Model 66A 12064, Waterbury 20, Conn.

in temperature. Heating of the extension wire is supposedly compensated for. Thus the accuracy of temperature measurements at the bulb are not affected by temperature differences or changes anywhere along the wires. Resistance thermometers are widely used because of the following advantages; remote recording, high sensitivity, small dimensions and fast response. The thermometers are metallic and usually made from platinum, nickel or copper. The relation between resistance and temperature for the bulb can be expressed as:

$$R = Ro\ (1 + aT + bT^2 + \text{-----}) \qquad (1)$$

Where Ro is the resistance at $0^{o}C$, T is temperature in ^{o}C, and a and b are constants. This relation is almost linear if the temperature is small. If Eq. (1) is replaced by the linear relation:

$$R = Ro\ (1 + aT) \qquad (2)$$

it can be shown that the maximum temperature error in the temperature interval 10-40^{o}C is less than 0.4^{o}C.[2] This value applies strictly to a platinum bulb but a similar one can be derived for any other metal.

Electrical resistance thermometers, manufactured by the Foxboro[3] Company were mounted on the Calgary Tower. The sensors are housed in aspirated shields for adequate ventilation and protection from direct sunlight. The recorder is of a balanced bridge type.

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[2] W.E.K. Middleton and A.F. Spilhaus, Meteorological Instruments, University of Toronto Press, Toronto 1953, p. 84.

[3] Model No. DB-23S-26W, Foxboro Co., Lasalle, Que.

The A.I.S.I. Smoke Sampler

The equipment used is an automatic spot sampler developed by the American Iron and Steel Institute[4]. In this instrument air is drawn through a filter tape which is held firmly by a clamp. After the required sampling time, in this case two hours, the clamp is released and a fresh area of filter is moved into the sampling head. The soiled spots are evaluated by measuring the optical density (O.D.) of the spot with a photometer. This is set to read 100% transmittance through a clean filter. A value can then be read for the soiled spot. The optical density can be written:

$$O.D. = \log \frac{Io}{I} \tag{3}$$

Where Io is the intensity of light transmitted through clean tape and I is the intensity of light through soiled tape. As this is a non-linear relation caution must be observed in interpreting samples which fall below about 50% light transmission. Above this value the relation is approximately linear. For comparison with samples taken from other places the optical density is converted to a unit called the COH unit defined as:

$$1 \text{ COH unit} = 100 \times O.D. \tag{4}$$

COH is an abbreviation for "coefficient of haze". The density of the filter stain depends on the volume of air drawn through the tape. Therefore the volume is divided by the area of the sampled spot to

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[4] Model No. F2, Research Appliance Co., Allison Park, Penn.

obtain a linear unit of air.

$$L = \frac{t \times \bar{Q}}{A} \qquad (5)$$

Where t is the sampling time in minutes,

$\bar{Q}$ is the average flow rate for the sampling time in $(\text{feet})^3 \text{min}^{-1}$, and

A is the sampling area in $(\text{feet})^2$.

For convenience the quantity of air is expressed in thousands of linear feet.

$$L = \frac{t \times \bar{Q}}{1000 \times A} \qquad (6)$$

Thus:

$$\text{COH units per 1000 linear feet} = \frac{100 \times \text{O.D.}}{L} = \frac{10^5 \times \text{O.D.} \times A}{t \times \bar{Q}} \qquad (7)$$

For the samplers used in this investigation the following values are valid:

$t = 120$ minutes

$\bar{Q} = 0.25$ cfm

$A = 0.0054$ ft.^{2} (1 inch diameter)

Substituting these values in Eq. (7) gives:

$$\text{COH/1000 ft} = \frac{10^5 \times \text{O.D.} \times 0.0054}{120 \times 0.25} = 18 \times \text{O.D.} \qquad (8)$$

Thermographs[5]

Seven thermographs were installed in Edmonton and Calgary for measuring the horizontal temperature distributions. These instruments employ a bimetal element consisting of a compound strip of metal, formed by welding together two bars of different metals. The resulting strip bends as its temperature changes, because of the difference in expansion of the two metals. The deformation is then transmitted through a linkage system to a recording pen. The data are recorded on a seven day clock and drum assembly whose chart is printed in one degree intervals over a range of -40°C - +40°C. The instrument cover which is finished in white enamel provides shielding from solar radiation while allowing free movement of air around the sensing element. Before being put into operation all instruments were carefully calibrated against an aspirated Assman psychrometer and yielded a maximum error of ±0.3°C in the temperature range of -26°C - +19°C. The instruments are at present possibly reading up to 6-8°C too high under conditions of light wind and bright sunshine. These large errors are attributed to inadequate ventilation. Other large errors occasionally resulted from acts of vandalism and accidental damage to the instruments. In the absence of strong solar radiation comparisons with standard instruments showed differences of ±0.5°C or less.

Mobile Unit

Instrument used for the Temperature Traverses

In addition to the thermographs, temperature traverses were taken to obtain a more complete picture of the horizontal distribution

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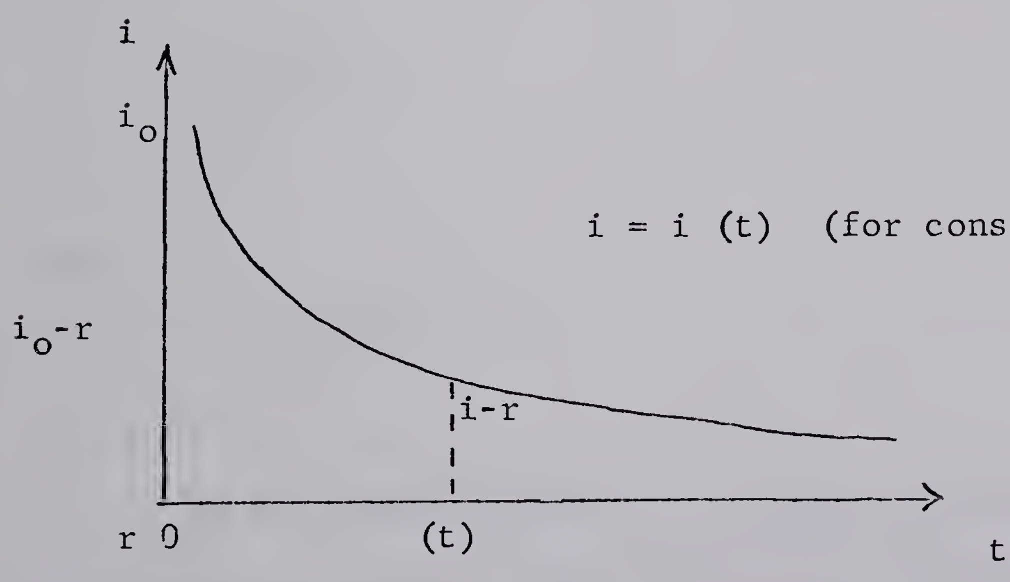
[5] Thermograph No. OT04, Eiwa Seiko Company, Osaka, Japan.

of temperature. As the mobile unit is moving, it was necessary to have an instrument that responded quickly to small changes in temperature. It was thought that an electrical resistance thermometer would meet this requirement. Therefore such a thermometer, manufactured by the same company as the Calgary Tower thermometers, was mounted on top of a van belonging to Geoscience Research Associates Limited. The instrument was shielded from direct sunlight. Sufficient ventilation is provided for when the van is moving. The sensor is connected with a recorder placed inside the van where it can be easily read by the driver.

The Lag Coefficient of the Thermometer

When a thermometer of any sort at a certain temperature is placed in a medium at a different temperature it does not immediately take up the temperature of the medium but approaches it asymptotically at a rate which depends on the materials and dimensions of the thermometer and also on the properties of the medium itself.



The change in the indication of the thermometer with time is given by the differential equation:

$$\frac{di}{dt} = -\frac{1}{\alpha}(i - r) \tag{9}$$

where i is the indicated value, r is the true value, and α is the lag coefficient with dimensions of time.

Let us now assume that α is a real constant and also that the temperature of the medium does not change. Then integration of Eq. (9) gives:

$$\int_{i_o}^{i} \frac{1}{i - r} \cdot \frac{di}{dt} = -\frac{1}{\alpha}\int_{o}^{t} dt \tag{10}$$

where i_o is the value of i at time zero

$$\ln \frac{i - r}{i_o - r} = -\frac{t}{\alpha} \tag{11}$$

$$\frac{i - r}{i_o - r} = e^{-t/\alpha} \tag{12}$$

Put

$$\frac{i - r}{i_o - r} = y$$

Then

$$y = e^{-t/\alpha} \tag{13}$$

If the substitution $t = \alpha$ is done in Eq. (13) we see that the lag coefficient is the number of seconds required for the difference of

temperature to be reduced to $e^{-1} = 1/e = 1/2.718 = 37\%$ of its initial value.

The lag coefficient α is highly dependent on ventilation and decreases rapidly with increasing ventilation. As the lag coefficient is not known in this case it has to be calculated. According to Newton's law of cooling the rate of change of temperature (θ) for the thermometer can be written:

$$K(\theta - T) = -MC\frac{d\theta}{dt} \qquad (14)$$

where M is the mass of thermometer, C is the specific heat of the thermometer, and K is the coefficient of dissipation, and

T is the air temperature

Eq. (14) and Eq. (9) combined gives:

$$\frac{d\theta}{dt} = -\frac{K(\theta - T)}{MC}$$

$$\frac{d\theta}{dt} = -\frac{1}{\alpha}(\theta - T)$$

Then:

$$\alpha = \frac{MC}{KL} \qquad (15)$$

where L is the length of the probe

Thus the lag coefficient contains the dissipation coefficient of the thermometer as a factor and is also a function of the specific heat of its material.

The bulb is made of brass coated with nickel which is estimated to be not over 3% of the total weight. The bulb is cylindrical with diameter 0.635 cm. and length 26 cm. The difference in density for the two metals is less than 0.4 gcm^{-3}, the difference in specific heat is

0.018 cal. $g.^{-1}$ $deg.^{-1}$ and the difference in the dissipation coefficient is 0.16 cal. $sec.^{-1}$ $deg.^{-1}$ $cm.^{-1}$. In spite of the large difference in the dissipation coefficient the author chose to base all calculations on brass alone. The mass of the bulb can be calculated from:

$$M = \rho V = \rho \pi R^2 L \tag{16}$$

which gives $M = 70$ g.

The specific heat for brass at 20°C is 0.09 cal. $g.^{-1}$, its density $\rho = 8.5$ $g.cm.^{-3}$ and its dissipation coefficient at the same temperature is 0.30 cal. $sec.^{-1}$ $deg.^{-1}$ $cm.^{-1}$.

The lag coefficient α can then be calculated according to Eq. (15):

$$\alpha = \frac{70 \times 0.09}{0.3 \times 26} \simeq 0.7 \text{ sec.}$$

Thus the thermometer will register 63% or 1/e of a sudden temperature change in 0.7 sec.

As an example of the thermometer's efficiency consider a sudden temperature change of 1°C. How far can the van run before 90% of the change is recorded?

The time it would take to do this can be obtained from Eq. (13):

$$e^{-t/\alpha} = \frac{1}{10}$$

$$e^{t/\alpha} = 10$$

and

$$t = \alpha \ln 10 = 2.3\,\alpha = 1.61 \text{ sec.}$$

If the van is driven at maximum speed 30 m.p.h. the distance covered would be:

$$\frac{30 \times 1.609 \times 10^3 \times 1.61}{36 \times 10^2} \simeq 22 \text{ m} \quad (72 \text{ ft.})$$

This maximum distance is assumed to be small enough for the traverses.

Location and Physiography of the Edmonton Region

Edmonton with a population of 394,000 (1968) and an area of 85 square miles (1966) is the capital of Alberta, located at latitude 53°33' North and longitude 113°30' West. The valley of the North Saskatchewan is the main channel in the area. It cuts across the city from southwest to northeast. The river valley is deep and twisting, ranging in width from half a mile in the southwest to a mile in the center of the city. The average depth is 160 feet, but in places it is over 200 feet deep.

The angle of slope of the river valley varies from 5° in the university area to 45° at Grierson Hill.

Several tributary ravines enter the main valley from both sides.

The residental area of the city is mainly of low density (<50 persons per net acre) with exception of the city core which can be classified as being of medium density (50-89 persons per net acre)[6]. The houses in these areas are generally one- and two-storey homes and are rather close to one another. The Commercial Districts consisting

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[6]From City Land Use Map, 1965, City Planning Office, Edmonton.

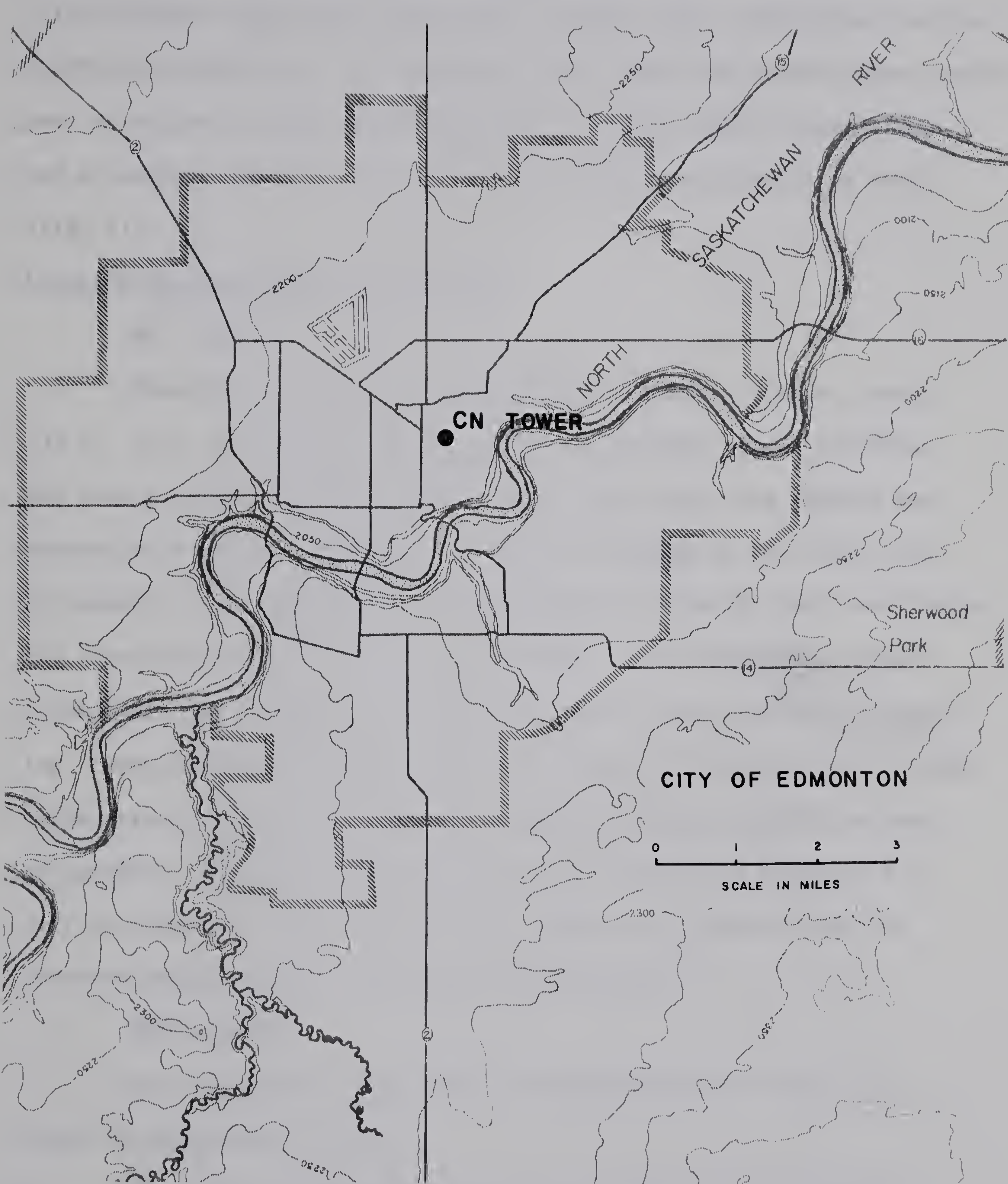

Figure 1

Physiography of Edmonton Region and Location of CN Tower

of closely spaced and taller buildings are located in the core of the city, and also along 82nd Avenue and in Jasper Place. Industries are concentrated to the east, south and north-west. There are several open spaces, such as ravines, parks, recreation areas, sports fields, playgrounds and an airport, amounting to roughly 12% of the total built up area, (Fig. 1).

<u>Location of the Edmonton Instruments</u>

CN - Tower

Electrical resistance thermometers at three different levels (15 m., 57 m. and 113 m.) were installed on a large office building (CN Tower) located in downtown Edmonton. The lowest and highest were mounted on 8 ft. booms projected from the building on the north wall. The sensors were housed in aspirated shields to provide good ventilation and protection from direct solar radiation. The intermediate level thermometer was placed in an air intake on the east wall of the building. Data collection was started on a continuous basis on June 1, 1967. Calibration carried out at monthly intervals showed no drift or loss of accuracy. However, a study of vertical temperature profiles for July and December, 1967, showed some evidence to indicate that the observed values at 57 m. were not representative[7].

Thermographs

The locations of the seven thermographs had to fulfill at least the following criteria:

a. They had to be placed on open areas away from buildings to

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[7] Geoscience Research Associates Limited, <u>Annual Report: Investigation into Air Pollution in Calgary and Edmonton</u>. Edmonton, 1968.

minimize the effect of heat radiation.

b. At the same time they had to be placed sufficiently close to a continuously attended building to minimize damage by vandalism.

c. Last but not least, they had to be distributed in such a way as to effectively measure the temperature differences as one approaches the city center from the outskirts and so give an indication of the intensity of the heat island.

The following places were selected: (Fig. 2)

#1 1160 River Valley Road

#2 City Hall, 100 Street and 103 Avenue

#3 University of Alberta Campus

#4 11504 - 37B Avenue

#5 Jasper Place High School

#6 12735 - 101 Street

#7 6625 - 101 Avenue

Continuous temperature records were started in January, 1968. As unit #3 was often subjected to vandalism it was moved to 11333 -73 Avenue on October 3, 1968.

Air Samplers

Since August, 1964, there have been six A.I.S.I. samplers operating in the city, all of which were installed by the Department of Health of the Province of Alberta. The locations of these stations are: (Fig 3)

#1 CN Tower

#2 Administration Building (commercial)

#3 117 Avenue - 147 Street (industrial)

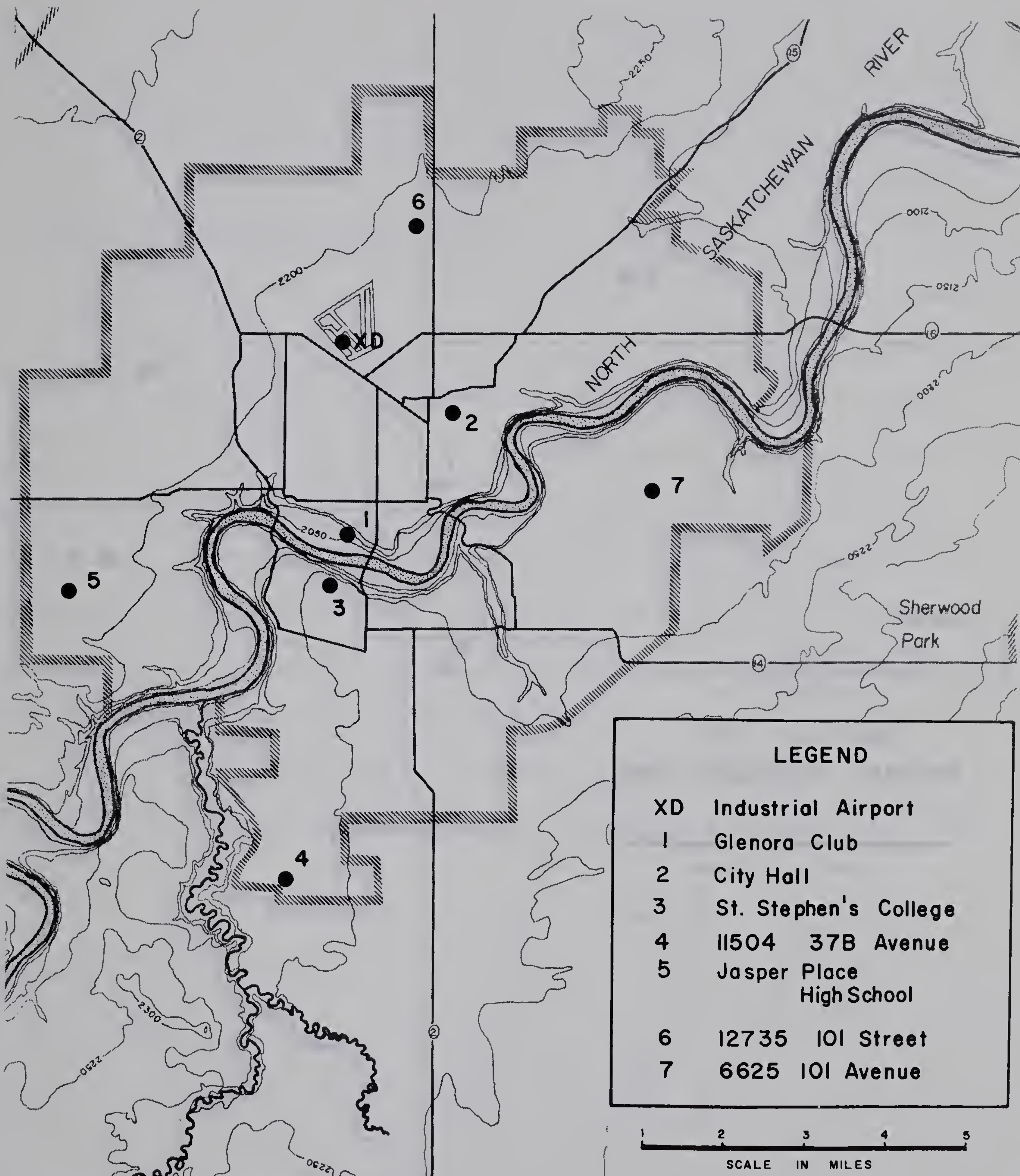

Figure 2

Location of Edmonton Thermograph Stations

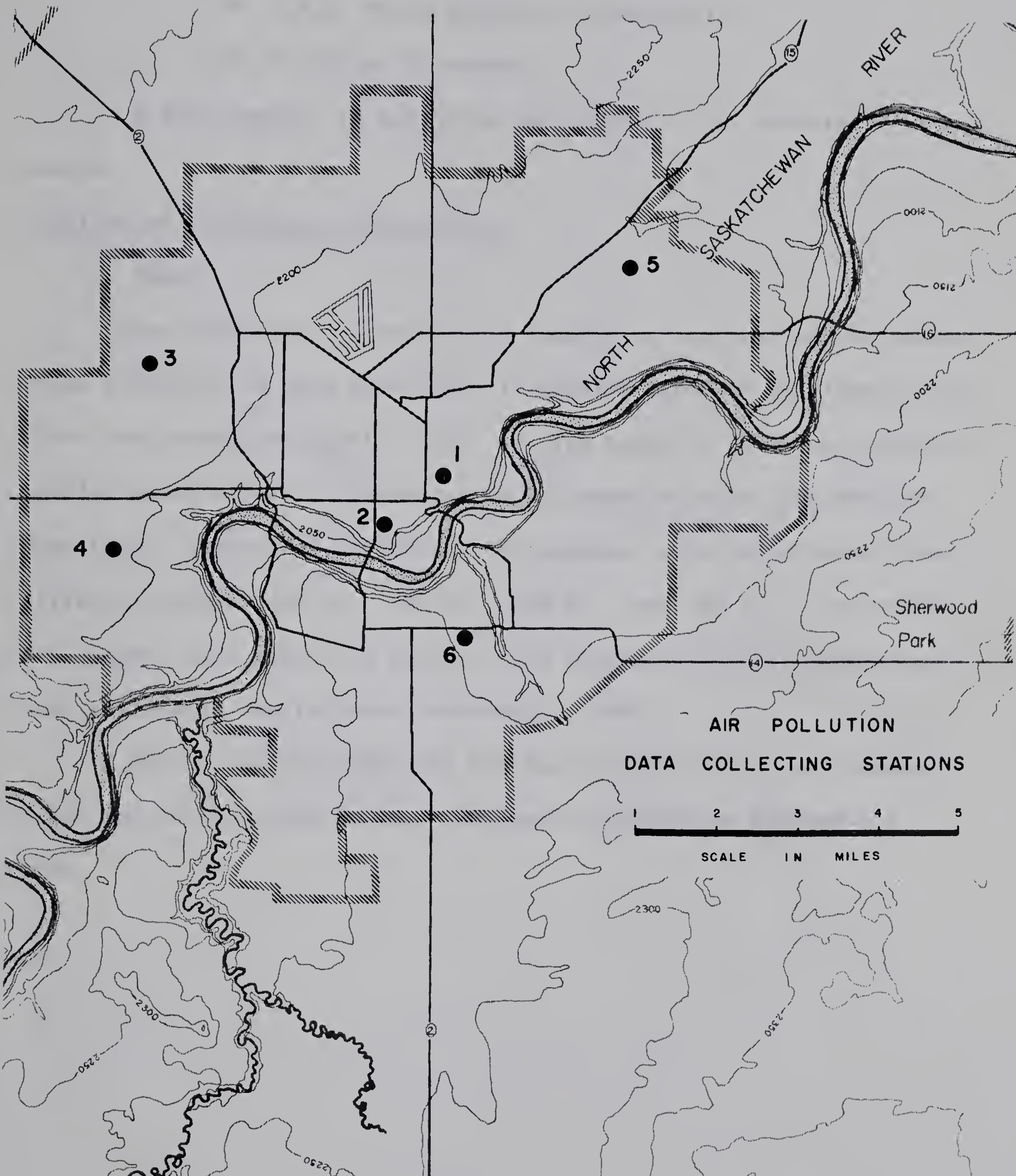

Figure 3

Edmonton Air Pollution Data Collecting Stations

#4 Sherwood School (residential)

#5 C.N.R. North Edmonton (industrial)

#6 97 Street 80 Avenue

A data summary is published each month by the Department of Health.

Location of the Calgary Instruments

Tower

The data tower in Calgary is located at the west end of Bonnybrook Bridge in an open area which is grass-covered, at an elevation of 3,345 feet above sea level. (Fig. 4) The tower is of three-cornered tubular metal construction measuring 18 inches on each side and 300 feet high. Electrical resistance thermometers were installed at four different levels (10 ft., 100 ft., 200 ft., and 300 ft.). As on the CN - Tower, each sensor is housed in an aspirated shield. Continuous data collection was initiated on March 1, 1968.

In the initial stage the 300 feet sensor showed considerable drift due to poor ventilation. This was corrected on September 4, 1968.

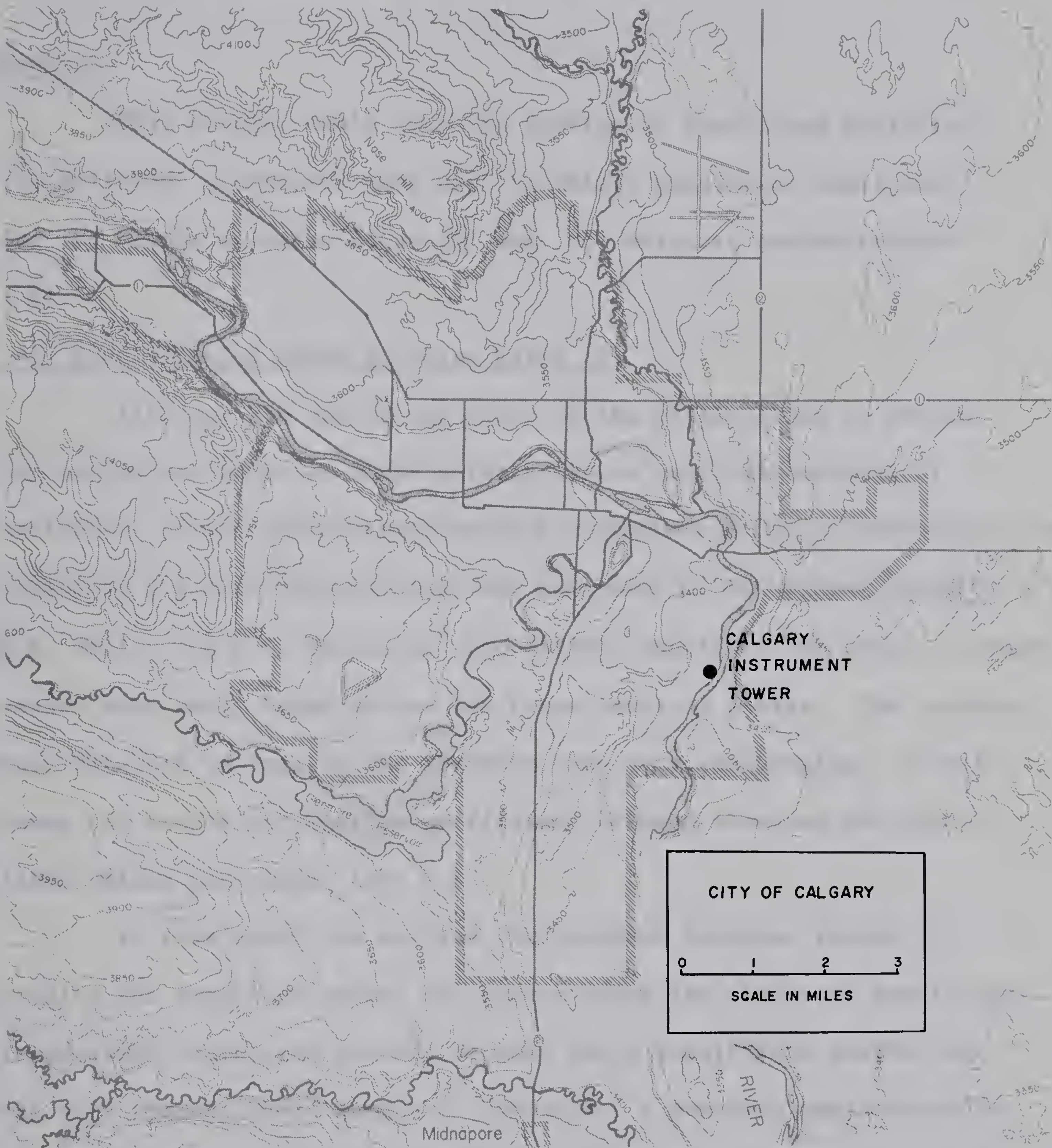

Figure 4

Location of Calgary Instrument Tower

CHAPTER II

PREDICTION OF SMOKE IN EDMONTON

General

This chapter deals with the problem of predicting pollution. Two different procedures were used to obtain prediction equations for a) smoke emission rates (Q) and b) absolute concentrations (χ).

a) Prediction of Smoke Emission Rates (Q)

Although the author was aware of the difficulties in obtaining useful estimates of smoke emission rates using meteorological variables, it was nevertheless decided to apply a multiple discriminant analysis to the data. Similar work has been done in the United States by e.g. M.E. Miller and G.C. Holzworth[1] who derived equations for source strength versus mean daily temperatures for three American cities. The results they obtained in testing the formulae were very encouraging. In all cases the simple correlation coefficient between observed and calculated values was higher than 0.8.

In this study the derived discriminant function failed to predict the output of smoke, the reason being the choice of predictors. Temperature variations did not account for a significant portion of the variation of smoke output in Edmonton. A possible explanation for this is that space heating, which is temperature dependent, is not a major source of smoke, due to the use of natural gas. The slight

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[1] M.E. Miller and G.C. Holzworth, An Atmospheric Diffusion Model for Metropolitan Areas. Air Resources Field Research Office, ESSA Cincinnati, Ohio, 1967.

variation with temperature in output from combustion engines is not enough to be significant. A description of the analysis that leads to the three prediction equations is given below.

The technique of discriminant analysis was originated by R.A. Fisher in 1936 and later extended by J.G. Bryan to multiple variables. The method can be described as a multivariate statistical model which expresses a set of mutually uncorrelated discriminant functions as linear functions of a fixed set of predictors (independent variables). The functional relationships are determined from a sample such that the ratio of the between-group sum of squares to the within-group sum of squares is maximized for each discriminant function. In other words a criterion that maximizes the distance between the group means, and minimizes the spread of the points about the means, i.e. a criterion that maximizes the ratio:

$$\lambda_j = \frac{SSB(Y_j)}{SSW(Y_j)} \tag{1}$$

where

$$SSB(Y_j) = \sum_{g=1}^{G} n_g \; (\bar{Y}_{jg} - \bar{Y}_j)^2 \tag{2}$$

and

$$SSW(Y_j) = \sum_{g=1}^{G} \sum_{k=1}^{n_g} (Y_{jgk} - \bar{Y}_{jg})^2 \tag{3}$$

$$k=1, ----n_g$$

$$g=1, ----G$$

Mathematical Procedure[2]

Predictor Space

Let there be G mutually exclusive and exhaustive groups defined for the predictand variable. Assume there are P predictors denoted by X_p (p =1, --- P).

Let the number of observations in each group of the dependent sample be n_g (g = 1, ---G)

Let

$$N = \sum_{g=1}^{G} n_g \tag{4}$$

Determine the quantities:

The pooled within-group sum of squared deviations about the group means,

$$SSW(X_p) = \sum_{g=1}^{G} \sum_{k=1}^{n_g} (X_{pgk} - \bar{X}_{pg})^2 \qquad (p = 1, --- p) \tag{5}$$

and the sum of squared deviations between group means and the grand mean,

$$SSB(X_p) = \sum_{g=1}^{G} n_g (\bar{\bar{X}}_{pg} - \bar{X}_p)^2 \qquad (p = 1, --- p) \tag{6}$$

Also required are the sum of products within (SPW) and between (SPB) groups.

For example, for predictors X_p and X_q

($P,_q$ = 1, --- p ; where $p \neq g$)

$$SPW(X_pX_q) = \sum_{g=1}^{G} \sum_{k=1}^{n_g} (X_{pgk} - \bar{X}_{pg})(X_{qgk} - \bar{X}_{qg}) \qquad (p,_q = 1, --- P; p \neq q) \tag{7}$$

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[2]This section is a summary of R.G. Miller's article, "Statistical Prediction by Discriminant Analysis," Meteor. Monographs, Vol. 4, Amer. Meteor. Soc., 1962.

and

$$SPB(X_pX_q) = \sum_{g=1}^{G} n_g(\bar{X}_{pq} - \bar{X}_p)(\bar{X}_{pq} - \bar{X}_q) \qquad (p,q = 1, \text{---} P; \; p \neq q) \tag{8}$$

A pooled within-group matrix W is constructed from the derived quantities

$$W = \left\{ \begin{array}{lllll} SSW(X_1) & SPW(X_1X_2) & \text{---} & SPW(X_1X_{p-1}) & SPW(X_1X_p) \\ SPW(X_1X_2) & SSW(X_2) & \text{---} & SPW(X_2X_{p-1}) & SPW(X_2X_p) \\ \vdots & \vdots & & \vdots & \vdots \\ SPW(X_1X_{p-1}) & SPW(X_2X_{p-1}) & \text{---} & SSW(X_{p-1}) & SPW(X_{p-1}X_p) \\ SPW(X_1X_p) & SPW(X_2X_p) & \text{---} & SPW(X_{p-1}X_p) & SSW(X_p) \end{array} \right\} \tag{9}$$

Similarly a between-group matrix B is constructed as follows:

$$B = \left\{ \begin{array}{lllll} SSB(X_1) & SPB(X_1X_2) & \text{---} & SPB(X_1X_{p-1}) & SPB(X_1X_p) \\ SPB(X_1X_2) & SSB(X_2) & \text{---} & SPB(X_2X_{p-1}) & SPB(X_2X_p) \\ \vdots & \vdots & & \vdots & \vdots \\ SPB(X_1X_{p-1}) & SPB(X_2X_{p-1}) & \text{---} & SSB(X_{p-1}) & SPB(X_{p-1}X_p) \\ SPB(X_1X_p) & SPB(X_2X_p) & \text{---} & SPB(X_{p-1}X_p) & SSB(X_p) \end{array} \right\} \tag{10}$$

Discriminant Space

The multiple discriminant analysis procedure makes use of both W and B to determine a new set of functions Y_j $\{j = 1, \text{---} \min. (G - 1, P)\}$, which are linear in the original predictors X_p. The method involves 1) an inversion of W, 2) a pre-multiplication of B by the inverse of W, and 3) a determination of the eigenvalues and

characteristic vectors of the resulting matrix $W^{-1}B$.

This is obtained by equating to zero the derivative of Eq. (1) which is to be maximized.

Thus:

$$\frac{\partial}{\partial V_{jp}} (\lambda_j) = \frac{SSW(Y_j) \frac{\partial}{\partial V_{jp}} (SSB(Y_j)) - SSB(Y_j) \frac{\partial}{\partial V_{jp}} (SSW(Y_j))}{\{ SSW(Y_j) \}^2} = 0 \quad (11)$$

By definition:

$$Y_{jpk} = \sum_p V_{jp} X_{pgk} \quad (12)$$

Differentiating Eq. (2) with respect to V_{jp} gives:

$$\frac{\partial}{\partial V_{jp}} (SSB(Y_j)) = 2 \sum_g n_g (\bar{Y}_{jg.} - \bar{Y}_{j..}) \{ \frac{\partial \bar{Y}_{jg.}}{\partial V_{jp}} - \frac{\partial Y_{j..}}{\partial V_{jp}} \} \quad (13)$$

where one dot means summing over k and two dots mean summing over k and g.

From Eq. (12):

$$\frac{\partial \bar{Y}_{jp.}}{\partial V_{jp}} = \sum_k X_{pg} = \bar{X}_{pg.}$$

$$(14)$$

$$\frac{\partial \bar{Y}_{j..}}{\partial V_{jp}} = \sum_k \sum_g X_p = \bar{X}_{p..}$$

Substituting Eq. (14) into Eq. (13), again making use of Eq. (12) gives:

$$\frac{\partial}{\partial V_{jp}} (SSB(Y_j)) = 2 \sum_g n_g \{ \sum_p V_{jp}\bar{X}_{pg.} - \sum_p V_{jp}\bar{X}_{p..} \} (\bar{X}_{pg.} - \bar{X}_{p..}) =$$

$$2 \sum_g n_g \sum_p V_{jp} (\bar{X}_{pg.} - \bar{X}_{p..}) (\bar{X}_{qg.} - \bar{X}_{q..}) \qquad (15)$$

where q is a dummy index.

This last expression is by definition equivalent to (B) V_{jp}

Similarly:

$$\frac{\partial}{\partial V_{jp}} (SSW(Y_j)) = 2 \sum_g \sum_k \sum_p V_{jp} (X_{pgk}) - (\bar{X}_{pg.}) (X_{qgk} - X_{qg.}) = \qquad (16)$$

$$(W)\ V_{jp}$$

Eq. (11) can now be written:

$$\frac{\partial}{\partial V_{jp}} (\lambda_j) = SSW(Y_j) \frac{\partial SSB(Y_j)}{\partial V_{jp}} - SSW(Y_j)\ \lambda_j \frac{\partial SSW(Y_j)}{\partial V_{jp}} = 0 \qquad (17)$$

Thus:

$$\frac{\partial SSB(Y_j)}{\partial V_{jp}} - \lambda_j \frac{\partial SSW(Y_j)}{\partial V_{jp}} = 0 \qquad (18)$$

which with Eq. (16) and Eq. (18) gives:

$$(B - \lambda_j W)\ V_{jp} = 0 \qquad (19)$$

The eigenvalues (λ) are then obtained by solving the determinantal equation

$$|W^{-1} B - \lambda I| = 0 \qquad (20)$$

where I is the unit matrix.

The characteristic vectors (V_j) which represent the weights on the predictors are solutions of the equations:

$$\{W^{-1} B - \lambda_j I\}V_j = 0 \qquad (j = 1, \text{---} \min(G - 1, P)) \tag{21}$$

where I is the unit matrix.

The discriminant functions can now be written as

$$Y_j = V_{j1} X_1 + V_{j2} X_2 + \text{---}\ V_{jp} X_p \qquad (j = 1, \text{---} \min(G - 1, P)) \tag{22}$$

Predictors

In this study three predictors were selected, the selection being based on the ready availability of the data and on some experience. All three predictors were transformed into dummy variables to simplify calculations. Below follows a description of the predictors and the values they take when transformed.

Predictor X_1: Above or below monthly normal minimum temperature in ^oF. (based on a thirty year average). X_1 is assigned a 1 if less than or equal to the monthly normal minimum temperature, and 0 if it is greater than this temperature.

Predictor X_2: This predictor also makes use of monthly normal minimum temperature. X_2 is assigned a 1 if it is either much below or much above monthly normal minimum temperature, and a 0 if it is either slightly below or slightly above. Much above and much below were defined as normal minimum temperature plus 10°F or more and normal minimum temperature minus 10°F or more, respectively.

Predictor X_3: Wind direction. X_3 was assigned a 1 if the wind direction was from NW - N - NE, and a 0 in all other cases. Daily values were taken for six winter months, October through March (1967-68) and compared with the predictand. The data were readily available from the Monthly Meteorological Summary prepared by the Department of Transport (Canada) for the city of Edmonton.

Predictand

The predictand was chosen to be smoke emission rate, with units g. $cm.^{-2}$ $sec.^{-1}$.

As smoke emission data were not available they had to be calculated from a mathematical model relating smoke emission rate with concentration of smoke, mixing height, and wind speed as follows:

Assuming a uniform smoke concentration within a box-like volume, and assuming a constant smoke production rate; the following result can be derived:[3]

$$X = \left\{ X_o \left(\frac{h_o}{h}\right) - \frac{QL}{\bar{u}h} \right\} \exp\left(-\frac{\bar{u}t}{L}\right) + \frac{QL}{\bar{u}h} \tag{23}$$

When t approaches large values the concentration will reach a state of equilibrium:

$$X = \frac{QL}{\bar{u}h} \tag{24}$$

Solving Eq. (24) for Q gives:

$$Q = \frac{\bar{u}h\,X}{L} \tag{25}$$

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[3] S. Djurfors, " An urban pollution model", The Albertan Geographer, No. 4, University of Alberta, 1968 P. 65-68.

where $\bar{u}$ is the mean wind speed in cm. sec.$^{-1}$ in the layer under consideration, h is the mixing height in cm., χ is the ground concentration of smoke in g. cm.$^{-3}$, and L is the effective cross-city dimension parallel to the wind direction and varying with the wind speed. In this study L was taken to be constant with the value 128 x 10^4 cm. Assuming the city lapse rate to be dry adiabatic due to vigorous turbulent mixing, the mixing height is obtained as the intersection between the dry adiabat from the observed ground temperature in the city and the observed temperature profile over the country[4]. This can be stated mathematically as follows:

Let the country lapse rate be:

$$\frac{dT}{dZ} = -\gamma \qquad (26)$$

and let the city lapse rate (Γ — dry adiabatic) be:

$$\frac{dT}{dZ} = -\Gamma \qquad (27)$$

Integration from Z=0 to Z=h and substitution gives

$$T_x - T_o = h\,(\Gamma - \gamma) = h\,\alpha \qquad (28)$$

Thus:

$$h = \frac{T_x - T_o}{\alpha} \qquad (29)$$

where T_x is the city ground temperature and T_o is the country ground

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[4] P.W. Summers, An Urban Ventilation Model Applied to Montreal. Ph. D. thesis, Montreal, 1964, P. 106-109.

temperature. The concentration of smoke (χ) is given in COH-units which is a relative measure and so has to be transformed into metric units. Sullivan[5] found that the best expression for the calculation of smoke density from smoke stains of one-inch diameter was as follows:

$$M^1 = \frac{a\ (D \times 100)^b}{V^{0.67}} \tag{30}$$

where M^1 is mass of particles with diameter less than 10 microns in $\mu g.m^{-3}$. Here, D is the optical density by reflection, a is a constant equal to 33.0, V is air volume, and b is another constant equal to 1.24.

Thus:

$$M^1 = \frac{33.0\ (D \times 100)^{1.24}}{(120 \times 0.25)^{0.67}} = 3.38\ (D \times 100)^{1.24} \tag{31}$$

The optical density by reflection (D) is, however, related to the optical density by transmission (O.D.) in the following way:

$$D = \frac{43}{44} \times O.D. = 0.98 \times O.D. \tag{32}$$

From Chapter I (Eq. 8):

$$O.D. = (COH/1000\ ft.)/18.0$$

Substitution of the above relation and Eq. (32) into Eq. (31) gives:

$$M^1 = 3.38(98/18.0 \times COH/1000\ ft.)^{1.24} = 3.38(5.44 \times COH/1000\ ft.)^{1.24} = 27.6\ (COH/1000\ ft.)^{1.24} \tag{33}$$

M^1 refers only to the fraction of particles with diameter less than 10 microns. To involve all particles it is assumed that the fraction

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[5] J.L. Sullivan, The Calibration of Smoke Density. Presented at the 55th annual meeting of Air Pollution Control Association, Chicago, 1962.

of small particles on the average is 70% of the total mass of particles.

Thus:

$$M = 39.5 \quad (\mathrm{COH}/1000\ \mathrm{ft.})^{1.24} \tag{34}$$

where M is the total mass of particles in $\mu g.\ m^{-3}$.

Hourly readings of smoke concentrations were obtained from the Department of Health for each of the six sampling stations and were averaged over 24 hours. This was done to smooth the data as previous tests had shown that 2-hour and even 8-hour averages were poorly correlated from one station to another. In Table 1 are shown the simple correlation-coefficients with each pair of stations for 24 hour readings averaged over six winter months, October through March, 1967-68.

Table 1

Correlation Matrix of Smoke Sampling Stations

Stn. No.	Correlation Coefficients					
	1	2	3	4	5	6
1	X	0.44	0.29	0.17	0.23	0.19
2	0.44	X	0.48	0.45	0.45	0.47
3	0.29	0.48	X	0.29	0.62	0.30
4	0.17	0.45	0.29	X	0.33	0.41
5	0.23	0.45	0.62	0.33	X	0.41
6	0.19	0.47	0.30	0.41	0.41	X

The values are still quite small and it may be better to use longer time averages in the future. In spite of all this it was decided to use the 24-hour readings. These readings were then averaged over all stations to obtain a value supposedly representing the average daily smoke concentration in Edmonton. Making use of Eq. (25) the mean daily smoke emission rate (Q) was calculated. The predictand was

divided into three classes as follows:

$$Q_1 = (0 - 0.2) \times 10^{-10} \text{ g. cm.}^{-2} \text{ sec.}^{-1}$$

$$Q_2 = (0.201 - 0.5) \times 10^{-10} \text{ g. cm.}^{-2} \text{ sec.}^{-1}$$

$$Q_3 = (0.501 - 6.0) \times 10^{-10} \text{ g. cm.}^{-2} \text{ sec.}^{-1}$$

Discriminant Functions

The predictand classes were then compared with each predictor and either a 1 or a 0 was recorded. The group means, the grand means, the within-group sums, and the between-group sums were calculated. The following values were obtained:

Predictor 1: $\bar{X}_{11} = 0.132$

$\bar{X}_{12} = 0.097$ $\qquad \bar{X}_1 = 0.106$

$\bar{X}_{13} = 0.090$

Predictor 2: $\bar{X}_{21} = 0.347$

$\bar{X}_{22} = 0.125$ $\qquad \bar{X}_2 = 0.197$

$\bar{X}_{23} = 0.118$

Predictor 3: $\bar{X}_{31} = 0.069$

$\bar{X}_{32} = 0.069$ $\qquad \bar{X}_3 = 0.078$

$\bar{X}_{33} = 0.097$

$SSW(X_1) = 40.9536$

$SSW(X_2) = 63.3736$

$SSW(X_3) = 31.2600$

$SSB(X_1) = 0.1459$

$SSB(X_2) = 4.8852$

$SSB(X_3) = 0.0753$

$SPW(X_1X_2) = 13.1386$

$SPW(X_1X_3) = 10.5927$

$SPW(X_2X_3) = 13.6086$

$SPB(X_1X_2) = 0.8352$

$SPB(X_1X_3) = -0.0603$

$SPB(X_2X_3) = -0.3312$

The matrices W and B were constructed according to Eq. (9) and Eq. (10) and the matrix $C = W^{-1}B$ was calculated giving the following values:

$$C = \begin{Bmatrix} 0.001066 & 0.005565 & -0.000881 \\ 0.014837 & 0.086719 & -0.006205 \\ -0.008749 & -0.050233 & 0.005408 \end{Bmatrix} \tag{34}$$

Solving the determinantal Eq. (20) for λ gave the cubic equation:

$$\lambda^3 - 0.093193\lambda^2 + 0.000175\lambda - 0.00000001 = 0 \tag{35}$$

with the roots:

$\lambda_1 = 0$

$\lambda_2 = 0.091276$

$\lambda_3 = 0.001917$

The vectors V_j representing the weights on the predictors are the solutions of the linear homogeneous Eq. (21).

To obtain non-trivial solutions to a set of these linear homogeneous equations the following relation may be used:

$$V_j = (-1)^{i+j}A_{ij} \tag{36}$$

where A_{ij} = determinant of order 2 formed by deleting the row and column containing a_{ij}.

The values of the weights corresponding to the three cases are listed below:

Case 1 $\lambda_1 = 0$

$V_{11} = 0.000157$

$V_{12} = -0.000025$

$V_{13} = 0.000014$

Case 2 $\lambda_2 = 0.091276$

$V_{21} = 0.000522$

$V_{22} = 0.007738$

$V_{23} = -0.004581$

Case 3 $\lambda_3 = 0.001917$

$V_{31} = 0.000040$

$V_{32} = -0.000018$

$V_{33} = -0.000155$

Substituting these values into Eq. (22) gave the desired discriminant functions:

$$Q_1 = 0.000157\ X_1 - 0.000025\ X_2 + 0.000014\ X_3 \tag{37}$$

$$Q_2 = 0.000522\ X_1 + 0.007738\ X_2 - 0.004581\ X_3 \tag{38}$$

$$Q_3 = 0.000040\ X_1 - 0.000018\ X_2 - 0.000155\ X_3 \tag{39}$$

Each X_i $(i = 1,2,3)$ must be either 0 or 1; therefore the minimum value for Q_j $(j = 1,2,3)$ is 0 and the maximum value equals:

$$\sum_{i=1}^{3} V_i = S$$

For perfect predictors, S would take on a value very close to 1. Comparing this with equations (37-39) immediately rules out minimum temperature and wind direction as predictors for smoke emission rate. For example, consider Eq. (38) which seems to be the most powerful one. Here the predictors explain only about 0.4% of the total variation in Q_2 and so cannot be used. The described procedure can be said to be indirect as it involves (1) a calculation of the smoke emission rate (Q), and (2) an application of the calculated Q-values in the pollution model to obtain the level of smoke concentration. We shall now describe a method that circumvents the problem of deriving smoke production rates and predicts concentrations from meteorological parameters only.

b) Prediction of Absolute Smoke Concentrations (χ)

Linear multiple regression was applied to the data to obtain a prediction equation for daily smoke concentrations. This method is simple and does not require vast calculations. Compared with discriminant analysis it has the weakness of not accounting for interrelations between the variates. Perfect interrelationships between one or more of the variates will lead to a singular matrix that has no solution. However, as in most meteorological problems, the variates are only partially interrelated, and so introduce an error in the prediction equation whose nature is an over- or an under-estimation, depending on the correlation between the variates.

Variates

Three predictors were selected to explain the variation in smoke concentration in the city. Daily values of these predictors for six

winter months, October through March, 1967-68, were taken from Monthly Meteorological Summary, Department of Transport (Canada). The predictand, valid for the same period of time as the predictors, was taken from Air Pollution Survey, Monthly report, Department of Health. A listing of the variates and their units is given below:

X: Mean daily concentration of smoke (g. cm.$^{-3}$ x 10^{-12}). The initial set of data was obtained as in section a) of this chapter.

X_1: Mean daily wind speed (m.p.h.) as measured 10 m. above the ground. In the strict sense the data are valid only for the Industrial Airport in Edmonton.

X_2: Mean daily heat island intensity defined as the difference in temperature between the Industrial and International Airports (^{o}F). The individual values were obtained from:

1/2 (Tmax - Tmin)

X_3: Mean daily vertical temperature gradient (^{o}C(100m.)$^{-1}$). These standard units are obtained from readings at 17 m. and 112 m. on the CN Tower in downtown Edmonton.

Mathematical Procedure

We can write the regression equation in the general form:

$$Y = K_o + K_1X_1 + K_2X_2 + \text{----} K_nX_n \tag{40}$$

where K_o is an additive constant and K_i (i=1, --- n) are the weights on the independent variables to be determined from the data in the sample. This equation is the best linear relation suited to predict Y from X_i (i=1, --- n) and is obtained by the method of least squares such that

$\Sigma (Y^1 - Y)^2$ is a minimum. Here Y^1 are the observed values. The weights can be computed by solving simultaneously the normal equations.

$$
\begin{array}{l}
NK_o + K_1 \; \Sigma X_1 + K_2 \; \Sigma X_2 + \cdots K_n \; \Sigma X_n = \Sigma Y \\
K_o \; \Sigma X_1 + K_1 \; \Sigma X_1^2 + K_2 \; \Sigma X_1 X_2 + \cdots K_n \; \Sigma X_1 X_n = \Sigma X_1 Y \\
\quad \vdots \\
K_o \; \Sigma X_{n-1} + K_1 \; \Sigma X_{n-1} X_1 + K_2 \; \Sigma X_{n-1} X_2 + \cdots K_n \; \Sigma X_{n-1} X_n = \Sigma X_{n-1} Y \\
K_o \; \Sigma X_n + K_1 \; \Sigma X_n X_1 + K_2 \; \Sigma X_n X_2 + \cdots K_n \; \Sigma X_n X_n = \Sigma X_n Y
\end{array}
\tag{41}
$$

The computed sums were in this case:

$\Sigma X_1 = 1657.4$ $\qquad \Sigma X_2 = 452$ $\qquad \Sigma X_3 = 77.3$

$\Sigma X_1^2 = 17530.06$ $\qquad \Sigma X_2^2 = 2250$ $\qquad \Sigma X_3^2 = 193.55$

$\Sigma X_1 X_2 = 3428.9$ $\qquad \Sigma X_1 X_3 = 411.91$ $\qquad \Sigma X_2 X_3 = 282.7$

$\Sigma Y = 1479$ $\qquad \Sigma X_1 Y = 11947.2$ $\qquad \Sigma X_2 Y = 4271.1$ $\qquad \Sigma X_3 Y = 1009.28$

and the weights:

$$
\begin{aligned}
K_o &= 9.77 \\
K_1 &= -0.32 \\
K_2 &= 0.22 \\
K_3 &= 1.68
\end{aligned}
$$

Substituting the weights into Eq. (40) gives the desired functional relation:

$$\chi = 9.77 - 0.32 X_1 + 0.22 X_2 + 1.68 X_3 \tag{42}$$

Data Test

To test the stability of the data used, six consecutive random samples of size 90 by 4 were removed from the original 183 by 4 data matrix.

A complete analysis was applied to each set with the following result:

Table 2

Results of Data Stability Tests

Test	K_o	K_1	K_2	K_3	$R^2\%$	$r^2_{X_1}\%$	$r^2_{X_2}\%$	$r^2_{X_3}\%$
1	10.02	-0.34	0.33	1.12	32.4	73.8	8.6	17.6
2	11.62	-0.45	0.02	1.79	42.3	24.1	0	75.9
3	9.86	-0.31	0.06	1.74	38.7	17.1	0.3	82.4
4	10.02	-0.31	0.28	1.93	50.7	14.8	3.6	81.5
5	9.89	-0.37	0.30	1.13	41.0	77.6	10.2	12.2
6	11.11	-0.41	0.24	1.13	31.0	81.6	3.9	14.2
Mean	10.42	-0.37	0.21	1.47	39.4	44.7	4.3	51.0

In column five is given the total variation explained, expressed in percent. In column six, seven and eight are given the proportion of the variation of the dependent variable accounted for by each independent variable, also in percent.

Judging from the table the data show considerable stability with only minor variations in the weights. The mean weights are in fair agreement with those of Eq. (42).

The three independent variables together explain about 40% of the total variation in smoke concentration. Of the three, wind speed and vertical temperature structure were of equal importance, while the horizontal temperature gradient was not a significant predictor. Adding more variables might throw some light on the somewhat low correlation.

The importance of relative humidity to smoke concentration near the ground should be looked into. Improved data for the predictand may also change the picture. As of now, the correlation between the

the different sampling stations leaves much to be desired.

Test

It was stated above that the regression equation would explain about 40% of the total variation of smoke. To test the stability of the equation, an independent sample comprising one month of data (December, 1968) was selected. The independent variables were listed and Eq. (42) solved for X giving the daily mean concentration of smoke in Edmonton. These values were then compared with the observed values taken from Air Pollution Survey, Monthly report, Department of Health (Figure 5). To find out how much of the total variance the prediction equation could explain for the selected month ,the differences between the predicted and observed values were formed with the mean values for the two sets not removed. The variance of the differences was then calculated. This came out to $36(\mu g.\ m.^{-3})^2$. The total variation to be explained was found to be $37(\mu g.\ m.^{-3})^2$. Stated otherwise, the prediction equation was able to explain only about 3% of the total variation in smoke concentration. It was then suspected that the difference in the means between the two sets of data was to blame for the low value. In order to make the data independent of the mean this was removed from each set of data. The differences were again formed using this new set of data and the variance of the differences was once more calculated. This time the value came out to $20.0(\mu g.\ m.^{-3})^2$. With the means thus removed the prediction equation explains about 44% of the total variation in smoke concentration. This is in excellent agreement with the value (40%) obtained from the dependent sample. With some reservations because of the small test sample it can be said that the

Observed Mean daily smoke concentration (circles) and calculated mean daily smoke concentration (crosses) in micrograms per cubic meters in Edmonton for December 1968.

Figure 5

prediction equation is quite stable for daily variations but fails to show skill in predicting monthly mean smoke concentrations.

CHAPTER III

THE HORIZONTAL AND VERTICAL TEMPERATURE DISTRIBUTION IN EDMONTON AND CALGARY

Introduction

In this chapter the horizontal and vertical temperature distributions in Edmonton and Calgary are described. A few horizontal temperature traverses were analyzed and compared with the results obtained from the study of the thermograph data.

Many studies of urban climates have been carried out in the past few decades. Outstanding examples are the fundamental work by P.A. Kratzer[1] in his "The Climate of Cities", and G.A. De Marrais'[2] study of Louisville, Kentucky. The latter was used for comparative purposes in the present study. In 1962 W. Klassen did a comparative climatological study involving temperature, wind speed and humidity on the plain and in the river valley system in the Edmonton area[3]. A. Daniels studied the role of the urban heat island in Edmonton using horizontal temperature traverses[4].

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[1] P.A. Kratzer, The Climate of Cities, Am. Met. Soc. Boston, Massachusets: 1956, 221 p.p.

[2] G.A. De Marrais, Vertical Temperature Difference Observed Over an Urban Area. Am. Met. Society, Bulletin, Vol. 42, No. 8, August 1961, p. 548-554.

[3] W. Klassen, Micrometeorological Observations in The North Saskatchewan River Valley at Edmonton, Department of Transport, Cir-3652 Tec-408, May 7, 1962.

[4] A. Daniels, The Urban Heat Island and Air Pollution, Unpublished M.Sc. Thesis, University of Alberta, Edmonton, 1964, 144 p.p.

Thermograph Data

The collection of thermograph data was initiated on a continuous basis in January and February, 1968. In the analysis to follow it would have been preferable to work with a full year of data. As it turned out, however, November and December, 1968, were never processed because of lack of time and the January and February data had too many discontinuities to be worth considering. Station 3, located at St. Stephen's College on the campus of the University of Alberta, was often subjected to vandalism leaving data gaps of up to ten to fifteen consecutive days. Because of this it was decided to omit data from this station entirely. Occasional data gaps were filled in for the other six stations using data from the Industrial Airport. This procedure is far from perfect but will give a better estimate of mean values than if these gaps were left blank. The author was now left with eight months, March through October, 1968, of complete raw data for six different thermograph stations. It was known that most stations were reading too high on sunny days. As this radiation error caused by solar heating could be different for each station and difficult to estimate without extensive calibrations, it was decided to omit the hours 9 a.m. to 5 p.m. for every day. Mechanical errors due to vandalism, deviations in the procedure of changing charts, etc., were compensated for by applying a correction factor to the mean monthly temperature values. The correction factors were provided by Geoscience Research Associates, Limited. These factors, different for each month and each station, were obtained by comparing the raw data with the readings from the Industrial and International Airports in periods of continuous rain or snow. The standard deviation of the differences of ten hour means

in such periods was ±0.4°C. Table 3 lists the mean monthly values, the corrections and the corrected mean monthly values (°C.) for the six thermograph stations and the Industrial Airport.

The existence and intensity of a heat island over an urban area is best studied by measuring the difference in temperature between the city itself and its surroundings. There should exist a well marked positive temperature gradient as one approaches the center of the city from the outskirts. This difference in temperature is caused by differences in heat-storage capacity, differences between incoming and outgoing radiation due to pollution, and the excess of heat in the city due to human activities. On clear calm nights this difference is quite pronounced. With high winds and cloudy skies it will decrease accordingly. To find out whether there exists a significant change in temperature from one place to another a Student's t-test was applied to the corrected temperature data.

Statistical Approach

We wanted to show whether there exists a significant change in temperature from one place to another. If the Student t-test is applied to the data the following will hold: if the means of two samples differ from each other so that t is greater than a certain limiting value, depending on the degrees of freedom involved, it is extremely unlikely that the samples are random samples drawn from the same population. As any two samples which are compared are not independent random samples but are deliberately paired to reduce all differences other than the ones due to the effect being investigated the normal t-test for independent samples was ruled out. Instead the method of paired samples was

Table 3

Edmonton Thermograph Data

	I			II			IV			V			VI			VII			XD		
MONTH	RAW	CORR	CD	RAW	CORR	CD	RAW	CORR	CD	RAW	CORR	CD	RAW	CORR	CD	RAW	CORR	CD	RAW	CORR	CD
1968																					
Mar.	-1.3	+0.6	-0.7	0.2	+0.0	0.2	0.1	-1.2	-1.1	-1.2	+0.3	-0.9	-2.3	+1.7	-0.6	-2.4	+1.1	-1.3	0.1	+0.0	0.1
Apr.	2.0	+0.0	2.0	2.6	+0.0	2.6	3.6	-2.2	1.4	1.8	+0.3	2.1	2.7	-1.1	1.6	0.7	+1.1	1.8	3.1	+0.0	3.1
May	8.8	+0.2	9.0	9.7	+0.0	9.7	10.9	-2.2	8.7	9.1	+0.3	9.4	9.8	-0.6	9.2	7.9	+1.1	9.0	10.0	+0.0	10.0
June	12.5	-0.3	12.2	12.9	+0.0	12.9	14.5	-2.2	12.3	12.8	+0.0	12.8	12.7	+0.0	12.7	12.0	+1.1	13.1	13.4	+0.0	13.7
July	16.1	-0.3	15.8	16.6	+0.0	16.6	17.2	-2.2	15.0	15.6	+0.0	15.6	15.2	+0.3	15.5	14.2	+1.1	15.3	16.2	+0.0	16.2
Aug.	12.5	+0.8	13.3	13.2	+0.0	13.2	12.4	-0.6	11.8	11.9	+0.0	11.9	11.3	+1.1	12.4	10.6	+1.1	11.7	13.2	+0.0	13.2
Sept.	7.9	+0.8	8.7	10.0	+0.0	10.0	8.6	-0.6	8.0	8.4	+0.6	9.0	7.8	+1.1	8.9	7.8	+1.1	8.9	9.8	+0.0	9.8
Oct.	1.5	+0.8	2.3	3.8	+0.0	3.8	2.2	+0.0	2.2	2.2	+0.6	2.8	1.9	+1.1	3.0	1.6	+1.1	2.7	4.0	+0.0	4.0

used as follows[5].

Obtain the N differences between members of a pair:

$$d_i = X_{1i} - X_{2i} \tag{1}$$

where the subscript 1 refers to one sample and the subscript 2 to the other. On the null hypothesis that the samples do not really differ the expectation of d_i is zero.

If S^2 is the variance of the differences i.e.

$$nS^2 = \Sigma d_i^2 - N\bar{d}^2 \tag{2}$$

the quantity

$$\bar{d}N^{\frac{1}{2}} S^{-1} \tag{3}$$

has the Student-t distribution with n degrees of freedom.

Eq. (3) solved for fifteen different combinations gave the following t scores.

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[5] E.S. Keeping, Introduction to Statistical Inference, D. van Nostrand Company, Inc., New York. p. 185-186.

Table 4

Results of Student's t-test for Edmonton

Station Pairs	t - score
2,1	4.6
4,1	3.2
5,1	0.1
6,1	0.0
7,1	0.7
4,2	9.9
5,2	5.1
6,2	7.0
7,2	4.9
XD,1	4.5
XD,2	0.7
XD,4	15.2
XD,5	8.4
XD,6	9.4
XD,7	7.6

Entering tables with n = N-1 degrees of freedom gave the limiting values of t of 3.5 at the 1% confidence level and 2.4 at the 5% level. Thus every absolute value of t greater than these limiting values would show a significant difference in mean temperature at these levels[6].

Discussion

The t - score itself does not say which of the stations compared is the warmer. Therefore, the mean temperature for each station together with its standard deviation is listed in Table 5.

[6] Loc. cit.

Table 5

Edmonton Thermograph Data, Means and Standard Deviations

Station	Mean °C	SD °C
1	7.8	5.6
2	8.6	5.4
4	7.3	5.4
5	7.8	5.5
6	7.8	5.5
7	7.6	5.5
XD (Edmonton Industrial Airport)	8.7	5.3

Considering Station 1 first it is obvious from the tables that this station was not significantly warmer than the stations on the periphery in spite of its more central location. The only exception to this is Station 4, located in the southern suburbs. A possible explanation to the fact that the valley station is not warmer than the outer ones is that cold air at nights, and particularly on calm and clear ones, drains down the valley. Differences in density would then cause a cold stream of air to enter the system either in the SW or NE portions of the city. This stream will stay cold throughout the entire valley as no air from the city is likely to be fed in, again due to density differences. It can be supposed that this pattern is disturbed to some degree when overcast conditions are at hand and when the prevailing winds exceed a certain value. Thus Station 1 represents the river valley system which tends to separate the city into at least two heat islands. According to Table 4, Station 2, located at City Hall was significantly warmer than Station 1. Unfortunately Station 3, on campus, could not be included in the investigation but would very

likely have given the same result when compared with Station 1. It will be seen from Tables 4 and 5 that Station 2 was significantly warmer than any of the peripheral stations and this at the 1% confidence level. This was also true comparing XD with the peripheral stations. No significant difference in mean temperatures was found for the Stations XD and 2 although XD is situated at the edge of a large field.

Conclusion

There exists a significant change in temperature as one approaches the center of the city from the outskirts. This difference is caused by differences in heat-storage capacity, differences between incoming and outgoing radiation due to pollution, and the excess heat due to activities in the city. The urban heat island is divided into at least two parts by the valley of the North Saskatchewan River.

Temperature Traverses

In order to supplement the results from the analysis of the thermograph data a few temperature traverses were made over the city. A temperature traverse can be defined as a series of temperature measurements taken along a predetermined route. Such a method requires an instrument that is able to respond quickly to small changes in temperature. The thermometer used in the investigation is described in Chapter I. The calculated lag coefficient was considered small enough for the purposes of the study.

Because the traverses extended over several hours it was necessary to reduce all readings along the route to one constant time, to account for the general change in temperature with time. This was done as follows:

To the measured temperature at location i and at time t an amount was added or subtracted to give the temperature at the constant time c. This amount was calculated from readings at the Industrial Airport, and does not take into account the differences of the rate of change of temperature for different parts of the city. Also the general change in temperature had to be assumed linear in time. Despite these shortcomings, the method was found satisfactory for the purpose of this study.

Thus stated mathematically:

$$T_{i,c} = T_{i,t} + (T_{a,c} - T_{a,t}) \qquad (4)$$

where

$T_{i,c}$ is the temperature in ^{o}F. at the constant time c

$T_{i,t}$ is the measured temperature in ^{o}F. at location i at time t

$T_{a,c}$ is the Industrial Airport temperature in ^{o}F. at time c (on the hour)

$T_{a,t}$ is the Industrial Airport temperature in ^{o}F. at time t, determined by linear interpolation between two hourly readings. Time t occurs in this interval.

In the following, four cases are discussed:

Short discussion

Case 1. <u>October 10, 1968, 1115 - 1405 (Fig. 6)</u>

Current weather: Wind E to NW, 7 m.p.h., overcast.

In this overcast situation the horizontal temperature distri-

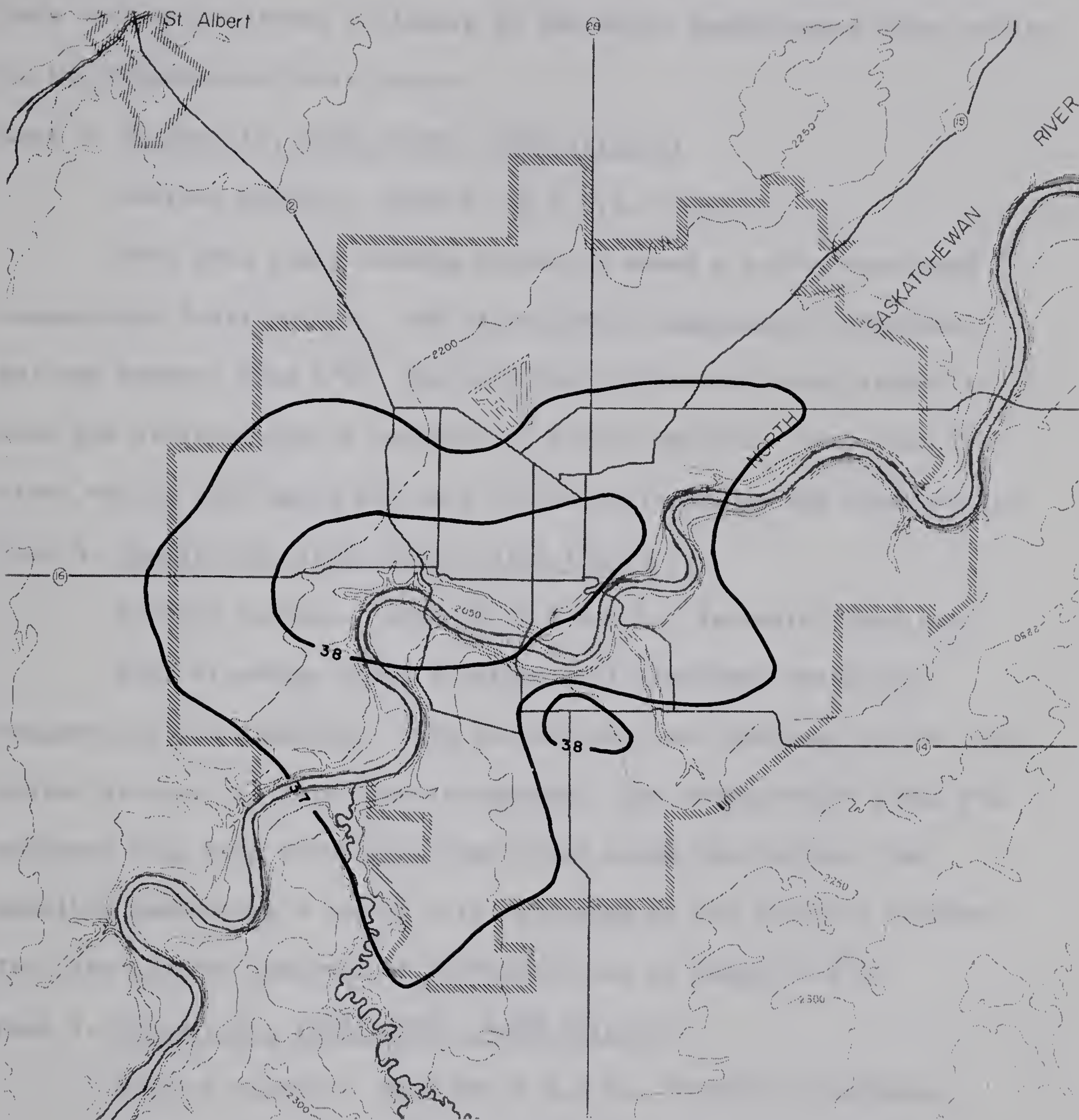

Figure 6

Isotherm Map for Edmonton, October 10, 1968
1115 - 1405 hours MST

bution showed only weak gradients in spite of fairly light wind speeds. Note the insignificant influence of the North Saskatchewan River valley on the temperature distribution.

Case 2. October 17, 1968, 0450 - 0650 (Fig. 7)

Current weather: Wind S, 14 m.p.h., clear.

Even this early morning situation shows a poorly developed temperature distribution. The city-country temperature difference was not greater than 2°F. The relatively high wind speed tended to make the distribution of temperature fairly uniform. Note that the river valley once again had very little influence on the distribution.

Case 3. January 18, 1969, 1815 - 2112 (Fig. 8)

Current weather: Wind NW, 2.8 m.p.h., Variable cloudiness.

This situation shows a rather well-developed horizontal temperature distribution. Note how the cold air drainage in the river valley divided the city into two sectors. The temperatures along the southern edge were much lower than those along the northern one, possibly indicating a lesser city influence on the southern suburbs. The city-country temperature difference was as large as 8°F.

Case 4. January 21, 1969, 0230 - 0400 (Fig. 9)

Current weather: Wind SW, 2 m.p.h., Variable cloudiness.

In this early morning situation note the pillow of warm air over the commercial area to the south and the insignificant influence of the river valley on the temperature distribution. Also in this case the city-country temperature difference amounted to 8°F.

Vertical Temperature Structure

Some of the properties of the vertical temperature structure

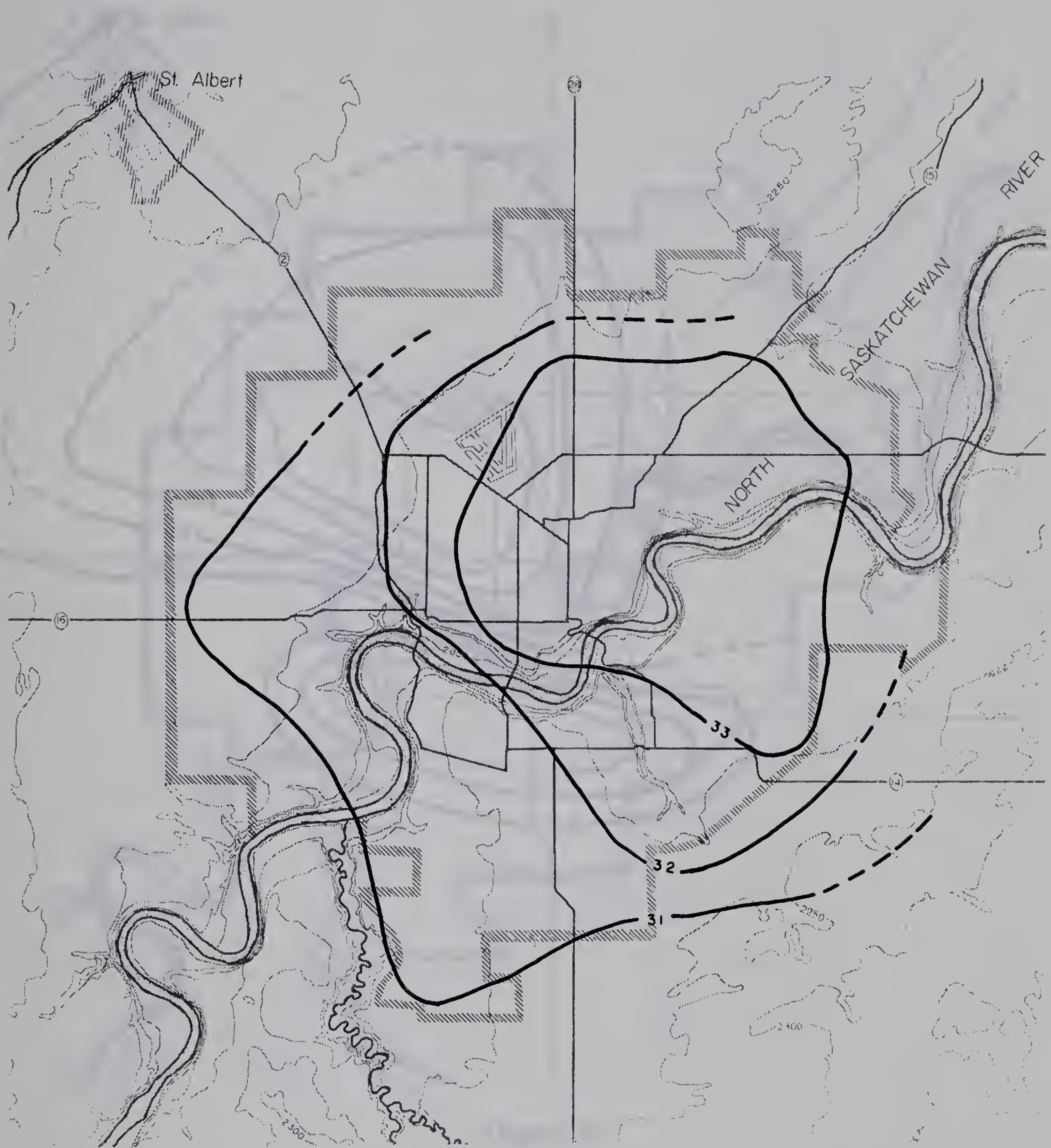

Figure 7

Isotherm Map for Edmonton, October 17, 1968
0450 - 0650 hours MST

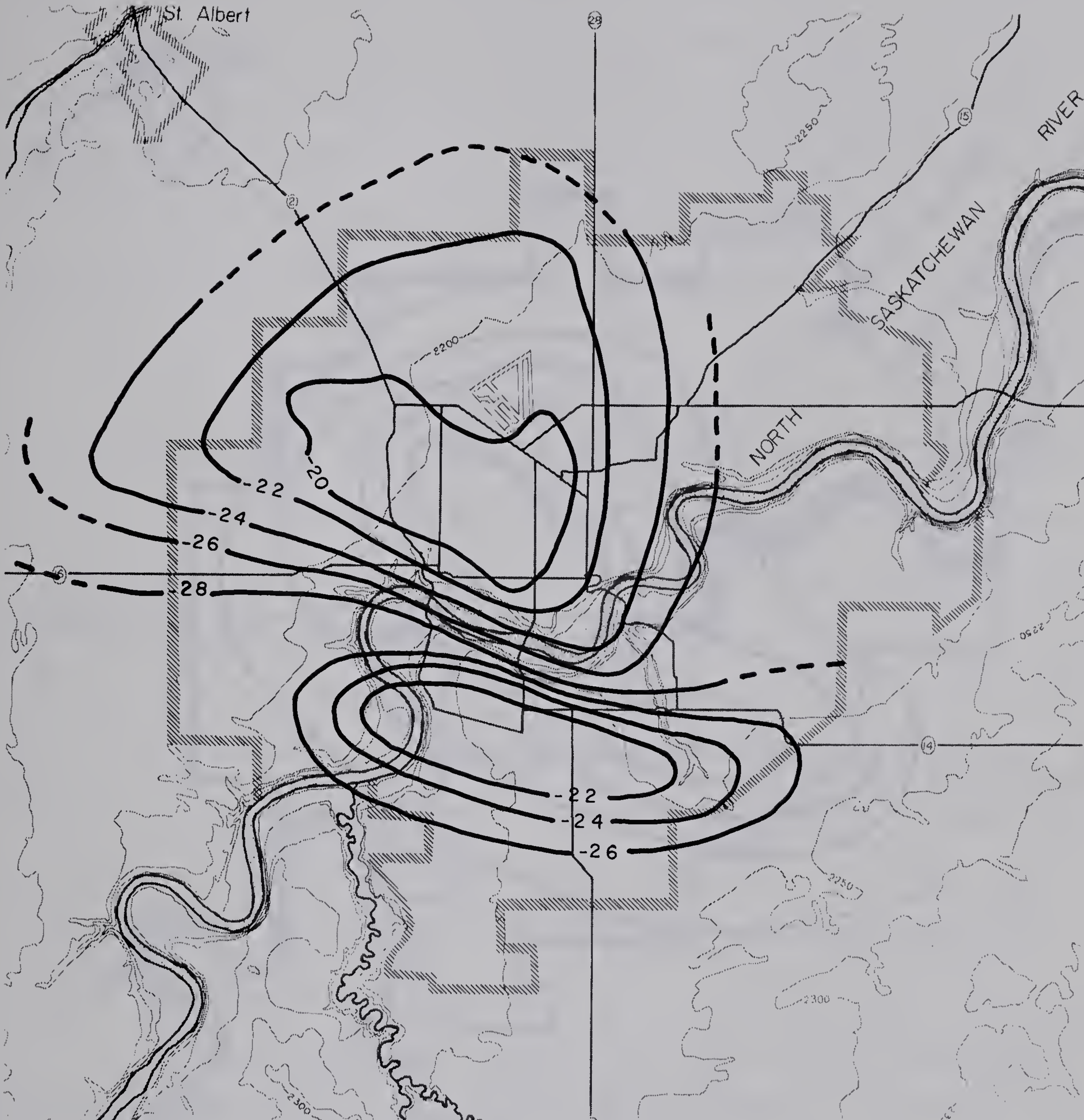

Figure 8

Isotherm Map for Edmonton, January 18, 1969

1815 - 2112 hours MST

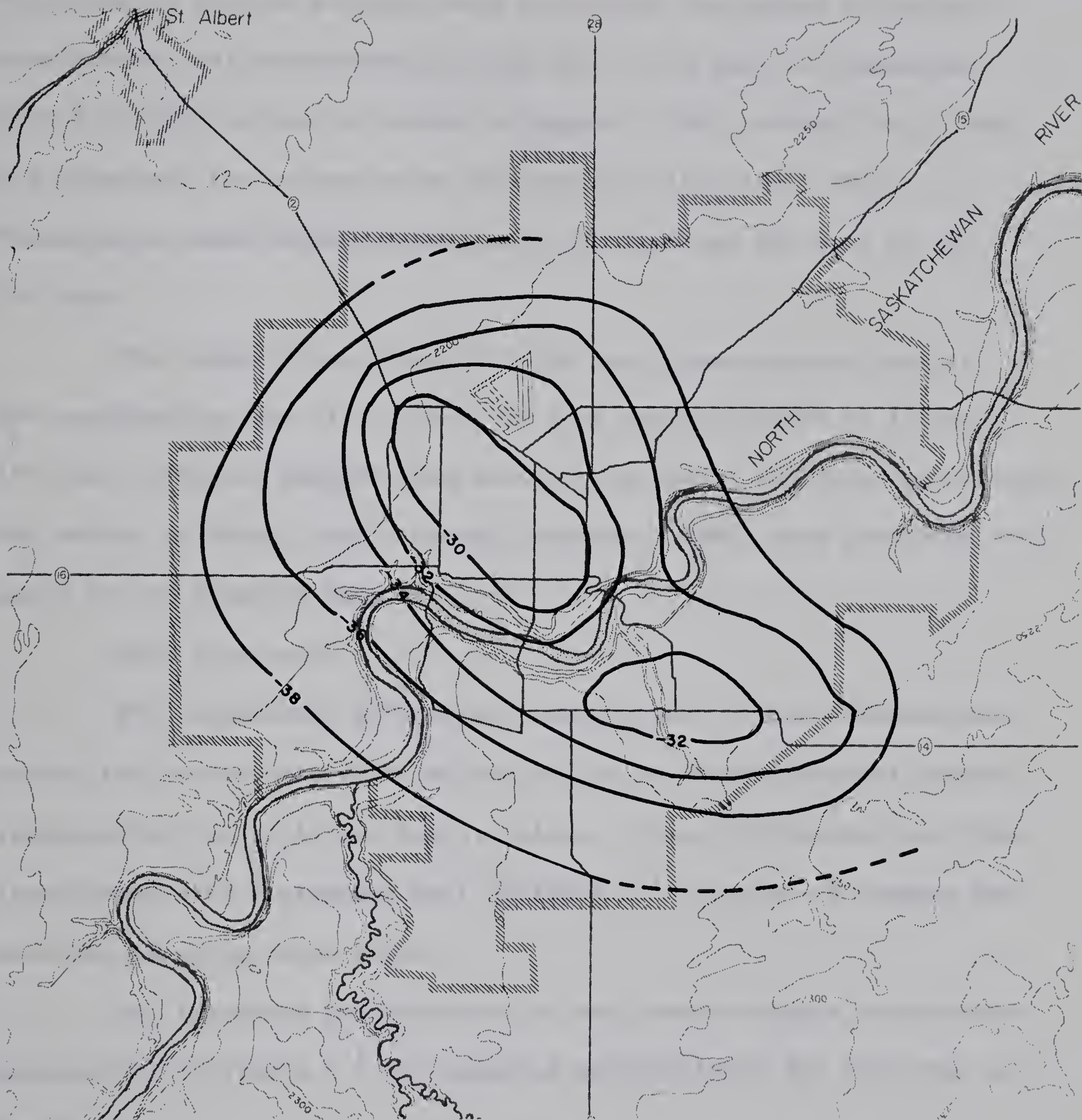

Figure 9

Isotherm Map for Edmonton, January 21, 1969
0230 - 0400 hours MST

over the cities of Edmonton and Calgary are described in this section. Two separate Fortran programs were written by the author to extract some statistical properties from the data. The data for Edmonton were collected during the months of August, 1967, through July, 1968, and represent the situation in the center of the city (Fig. 1). Thermometers were mounted at 49 feet, 186 feet and 369 feet on the CN Tower.

The Calgary Tower located in an open grass covered area in the southeastern end of the city had four sensors placed at 10 feet, 100 feet, 200 feet and 300 feet above the ground. The data representing the months of March, 1968, through September, 1968, were processed similarly to the Edmonton data (Fig. 4).

Data Processing

The temperature differences between each of the thermometers on the two towers were obtained and set up as two-dimensional arrays representing the daily and hourly values. These differences were then transformed into a standard unit $^{o}C(100\ m.)^{-1}$ in order to compare them with results from other sites.

The frequency distribution for each month using a temperature interval of $1^{o}C(100\ m.)^{-1}$ was computed and tabulated for each hour of the day.

For each layer the monthly mean values for each hour were calculated and graphed. As previously mentioned in Chapter I, the middle thermometer on the Edmonton Tower was not registering correctly and the author decided to omit the data in the analysis. Therefore the

present discussion is limited to a single layer of thickness, 320 feet (98 m.). It was found that the 300 foot sensor on the Calgary Tower was in error probably because of radiation effects. Therefore, only data from the lowest three levels were used giving a thickness of 190 feet or approximately 58 meters for the whole structure and 90 feet or approximately 27 meters for the lowest layer.

Analysis

The analysis is in two sections: A, Edmonton and B, Calgary.

A. Edmonton

As seen in Table 6, in which the average hourly temperature differences for alternate hours for each month are listed, near-adiabatic ($0.98^{o}C/100$ m.) conditions prevailed during the daylight hours in the summer; and isothermal, or a weak positive or negative, lapse prevailed throughout the rest of the year. The maximum positive lapse value occurred at noon ± 2 hours due to maximum incoming solar radiation at this time.

Temperature inversions of moderate strength occurred throughout the year at night and in the early morning hours, breaking approximately 2-3 hours after sunrise and forming again at sunset. The above-mentioned lag is constant throughout the year. Note that because stabilization began before sunset there was no lag in the formation of the inversions at this time. The maximum negative lapse occurred during the summer months around 4 a.m. and in winter about 5 a.m. The graphs in Appendix I reveal an interesting feature, namely that during the summer months, June, July, August, and to some extent Sept-

Table 6

Mean Hourly Temperature Gradients in °C$(100m)^{-1}$ for the months of August 1967 through July 1968 in Edmonton, Alberta. (49 ft. to 369 ft.) Curved lines through data indicate sunrise and sunset.

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
0	1.7	1.8	0.4	0.9	0.3	1.0	1.1	0.3	0.2	0.9	0.7	0.9
2	1.7	2.2	0.5	1.0	0.7	1.2	1.0	0.5	0.2	0.7	0.9	1.1
4	1.8	1.8	0.3	1.1	0.5	1.4	1.1	0.6	0.3	-0.5	0.9	1.2
6	1.3	1.6	0.5	1.1	0.5	1.3	0.7	0.7	0.1	-0.9	0.1	0.2
8	-1.1	0.2	0.3	0.9	0.6	0.9	0.6	0.9	-0.5	-1.5	-1.3	-1.4
10	-1.6	-1.2	-0.4	0.2	0.3	1.1	0.4	0.3	-0.7	-1.4	-1.6	-1.6
12	-1.4	-0.9	-0.3	0.2	0.0	0.8	-0.5	-0.3	-0.7	-1.1	-1.6	-1.7
14	-0.3	-0.2	-0.1	-0.3	-0.1	0.6	-0.3	-0.5	-0.6	-1.0	-1.0	-0.7
16	-1.1	-0.3	-0.2	-0.2	-0.1	-0.3	-0.2	-0.4	-0.6	-1.1	-1.3	-1.3
18	-0.7	0.1	0.2	0.2	0.2	0.4	0.3	-0.3	-0.5	-0.8	-1.0	-1.3
20	0.9	1.5	0.6	0.6	0.6	0.9	1.0	-0.1	0.0	0.2	-0.6	-0.7
22	1.7	1.9	0.5	0.5	0.6	1.0	1.2	0.2	0.1	0.7	0.2	0.7

ember and October, there is clearly a secondary maximum around 2 p.m. From a minimum at noon the temperature gradient dropped and quickly approached zero. The author suggests the following interpretation: the forming of convective clouds around midday will shield the earth enough to reduce the rate of heating of the ground. The lowest layer will cool off somewhat and a more homogeneous atmosphere will develop in the layer under consideration. To support this explanation the total amount of cumulus, heavy cumulus, cumulonimbus and stratocumulus were plotted for the hours 6 a.m. through 5 p.m. for the month of June, 1968. It is evident that these types of cloud are at a maximum between 1 p.m. and 3 p.m. (Fig.10).

Frequency distributions of the hourly vertical temperature gradient for the 15-113 m. layer on the CN Tower, for the months of August, 1967, to July, 1968, are shown in Appendix IVa. The data were converted to units of $^{o}C(100\ m.)^{-1}$ and grouped in classes of equal size of $1^{o}C(100\ m.)^{-1}$ each. A pronounced diurnal variation, with frequent superadiabatic gradients in the daytime, was evident for the summer months while it was not evident for the winter and transitional months. For the whole year the most frequent value of ΔT fell in the class -1 to 0 $^{o}C(100\ m.)^{-1}$, which can thus be taken as the statistical mode. DeMarrais found, in a study made in Louisville, Kentucky, that, whereas surface inversions occur regularly over non-urban areas, they were comparatively rare over Louisville[7]. He discovered that during more than half of the hours at night, a lapse rate between isothermal and

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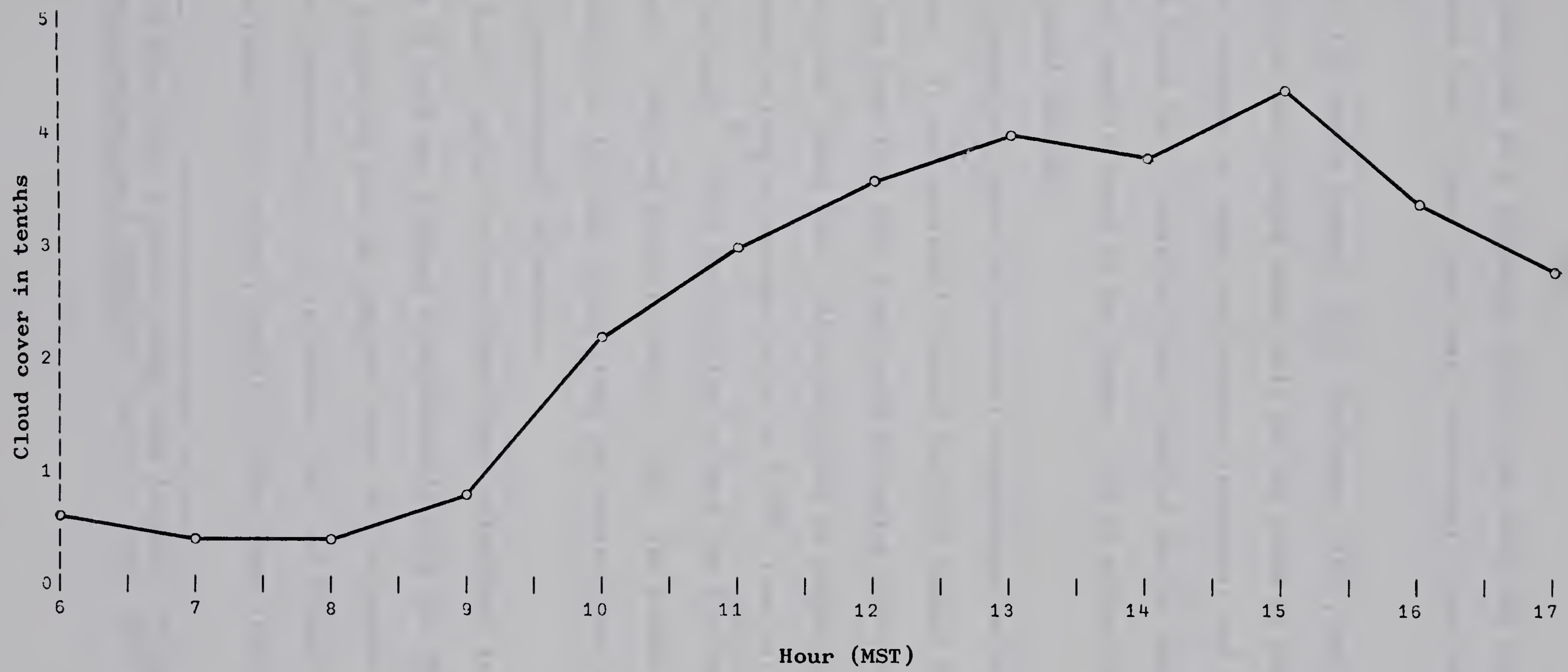
[7] DeMarrais, <u>op. cit</u>.



Total amount of cu, cu+, cb and sc in tenths plotted against hours of the day for the month of June 1968.

Figure 10

adiabatic was observed in a 150-meter thick layer over the city. In addition he found that a lower layer was considerably less stable than a deeper layer.

Except for the months August, 1967, September, 1967, and July, 1968, it is obvious that during about half of the hours at night there existed, on the average, a lapse rate between isothermal and adiabatic. Taken over the whole day, inversions were observed during approximately 37% of the total monthly hours in the summer, 52% in winter and 43% in the transitional seasons.

Graphs in Appendix II show the vertical temperature variation in the lowest layer. It was previously stated that the middle sensor was in error and thus data from this level were not going to be considered. However, it was later found that this error could be approximately corrected by substracting an average value of 0.7°F. from all individual readings at this level[8]. This was applied to data for the months of October-November, 1968, and February-March, 1969. The middle sensor is located at a height of 186 feet which gives the bottom layer a thickness of 137 feet or approximately 42 meters.

The mean hourly values for each month were calculated for the corrected sets of data and graphed simultaneously with the 98-meter layer. These graphs can then be compared with similar graphs from the city of Calgary (Appendix III). It is obvious that the Calgary daytime temperature decreases with height, rapidly in the lower layers and more

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[8]Report of Geoscience Research Associates Limited, "Investigation into Pollution in Calgary and Edmonton", April 1, 1967, March 31, 1968.

slowly at greater heights. At night the temperature increases with height , the gradient again being greatest in the lowest layer. These results are in close agreement with records obtained in open cultivated country[9]. Note that the Calgary Tower is located in the southeastern part of the city in a valley and on grass covered ground. The Edmonton graphs show a completely different picture. Here the curves are reversed at night so that the lower layer shows less stability than the deeper layer; this agrees with the findings of DeMarrais for Louisville, Kentucky. The CN Tower is located in central Edmonton and would more truly represent the situation over the city.

Interpretation

In the country, and thus also for Calgary, the morning sun will warm the ground and the air immediately above it much faster than any deeper layer of air. This will cause a much steeper negative temperature gradient in the lowest layers. It should be noted from the Calgary graphs that, except at midday, $\partial T/\partial t$ is very nearly constant with respect to height and time during the hours 1030 to 1400. After sunset the lowest layers will cool off quickly because of the greater loss in longwave radiation. A stronger inversion will thus build up in the layer close to the ground. The reverse situation at night in Edmonton is interpreted by the author as a heat island effect. There is apparently enough heat stored in buildings, streets and other objects during the daylight hours to make up for a good part of the outgoing long-wave radiation at night. Compared with the country situation

[9] O.G. Sutton, <u>Micrometeorology</u>, McGraw Hill, New York, 1953, p. 190.

this would of course develop a less stable lower layer.

Another interesting feature of the Calgary graphs is the tendency for $\partial T / \partial t$ to become independent of height for a short period around midnight, the numerical value being almost the same as that found around noon.

During any period of 24 hours of clear weather the temperature gradient changes sign twice, shortly after sunrise and before sunset. Best[10] found that the evening transition occurred at much the same time before sunset throughout the year but that the time of morning transition varied considerably from winter to summer, being later in the winter. The Calgary data cannot be used for comparison because no winter months were studied. However, attention is drawn to the fact that the two layers reach zero gradient at the same time at both transitions. The Edmonton graphs (App. I) representing city climate seem to have a seasonal variation. In the summer the morning transition occurred earlier than in the winter but also the evening transition had a seasonal variation occurring much later in the summer than in the winter. If the two-layer graphs from Edmonton are compared with the Calgary graphs it is seen that Edmonton shows similarities with Calgary in the morning but that the evening transition for the lower layer in Edmonton occurred about two hours later than that for the whole layer, which is obvious from the difference in sunrise - sunset times. This is most likely due to the excess of heat in the city over the country.

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[10] Loc. cit.

B. Calgary

As can be seen in Table 7, in which the average hourly temperature differences for alternate hours for each month are listed, adiabatic to superadiabatic conditions prevailed during the daylight hours throughout the seven months. The lower layer had the steeper gradient for reasons discussed earlier. The maximum positive lapse value occurred at about noon for both layers. Moderate to strong inversions occurred throughout the seven months at night and in the early morning hours, breaking and forming around sunrise and sunset respectively. Again the gradient in the lowest layer was most intense. The maximum negative lapse rate occurred in the summer around 2 a.m. for both layers and, in the transitional season, around 3 a.m. in the lower layer, and around 4 a.m. for the whole layer. The Calgary graphs have already been discussed in detail in the previous section.

Frequency distributions of the hourly vertical temperature gradients, for the bottom layer and the whole layer on the Calgary Tower, for the months March, 1968, to June, 1968, were constructed similar to those for Edmonton, and are shown in Appendix IVb. The data here are also in units $^{o}C(100m)^{-1}$ and divided into classes of equal size of $1^{o}C(100m)^{-1}$ each. A pronounced diurnal variation was evident in both layers. It was also evident that superadiabatic conditions were relatively more frequent in the lowest layer. The statistical mode for the whole layer was close to the wet adiabatic value of about $0.5^{o}C(100m)^{-1}$ in the lower layer. No comparison with the Edmonton data was possible because of differences in the thicknesses of the layers.

Table 7

Mean Hourly Temperature Gradients in °C(100m)$^{-1}$ for the months of March 1968 through September 1968, in Calgary, Alberta. Left portion represents the entire vertical structure of depth 61m., and right portion the bottom layer of depth 31 m. Curved lines through data indicate sunrise and sunset.

	Mar.	Apr.	May	June	July	Aug.	Sept.	Mar.	Apr.	May	June	July	Aug.	Sept.
0	1.4	2.0	1.1	1.4	2.8	1.8	3.6	2.2	3.0	1.6	2.4	5.1	3.5	5.5
2	2.1	2.2	1.4	1.7	2.0	1.7	2.8	3.0	2.6	2.0	3.0	3.5	3.2	4.7
4	1.7	2.6	1.4	1.4	1.6	1.7	1.3	2.6	3.9	1.6	2.4	3.0	2.8	2.0
6	1.6	1.3	-0.6	-0.2	0.8	1.7	1.9	2.4	1.8	-0.6	0.2	1.6	2.8	3.0
8	-0.4	-0.7	-1.6	-1.3	-1.2	-0.8	0.5	-0.4	-0.6	-1.8	-1.4	-1.4	-0.8	0.8
10	-1.4	-1.6	-2.3	-2.0	-1.8	-2.0	-1.7	-1.6	-2.0	-3.0	-2.6	-2.4	-3.0	-2.2
12	-1.7	-2.0	-2.5	-2.1	-2.1	-2.6	-2.4	-2.0	-2.6	-3.5	-2.8	-2.8	-3.7	-3.5
14	-1.6	-1.9	-2.3	-1.8	-2.2	-2.4	-2.0	-2.0	-3.0	-3.0	-2.4	-3.2	-3.5	-3.2
16	-1.4	-1.4	-1.8	-1.5	-1.9	-2.0	-1.6	-1.4	-1.4	-2.8	-1.8	-2.6	-2.8	-2.0
18	-0.4	-0.5	-1.1	-1.0	-1.2	-0.9	-0.7	0.4	-0.4	-1.0	-1.0	-1.4	-0.8	-0.6
20	0.5	1.0	0.5	0.2	0.8	1.0	2.7	1.4	1.6	1.0	0.8	1.6	2.2	4.9
22	1.2	1.5	1.2	0.9	3.1	1.5	3.3	1.0	2.6	2.0	1.6	4.9	2.6	5.1

Comparison with Data from Other Sites

Many vertical temperature difference data obtained from tower instrumentation in open country have been, and are currently being collected; data from Idaho Falls, Idaho, and Rye, Sussex, England, are included here[11]. As the data were presented in ^{o}F they had to be transformed into standard units $^{o}C(100\ m.)^{-1}$ in order to be comparable. The Idaho Falls Tower gave readings only for a layer 245 feet in depth or approximately 80 meters. The Rye Tower provided data from two layers, the lower being 105 feet or approximately 32 meters thick and the entire layer being 300 feet thick or approximately 92 meters.

Comparison of Edmonton and Idaho Falls, Idaho

The data in Table 8 are monthly average hourly temperature differences in $^{o}C(100\ m.)^{-1}$ based on observations from January, 1955, to May, 1958. Superadiabatic conditions prevailed throughout most of the daylight hours for the whole year and very strong inversions were legio at night and in the morning hours throughout the entire year. A comparison with Edmonton shows that the vertical temperature differences over the city and over a typical open country area were different. The difference in layer thickness should be considered but would in this case not change the overall picture.

Comparison of Edmonton and Rye, Sussex, England

The data in Table 9 are monthly average hourly temperature differences for the entire layer in $^{o}C(100\ m.)^{-1}$ based on observations from July, 1945, to June, 1948. The positive lapse rates in the winter and transitional seasons were somewhat larger than those observed in Edmonton, but the lapse rates for the summer months were quite similar.

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[11] DeMarrais, op. cit.

Table 8

Mean Hourly Temperature Gradients in $^{o}C(100m)^{-1}$ for the months of August through July in Idaho Falls, Idaho. Based on observations from January 1955 to May 1958 (250 ft. - 5 ft.). Curved lines through data indicate sunrise and sunset.

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
0	4.7	6.3	4.2	4.3	3.2	4.7	4.7	2.4	2.6	3.0	3.6	4.2
2	5.7	6.8	4.5	4.0	3.3	4.5	4.7	2.3	2.5	3.0	4.1	4.9
4	6.1	6.8	5.0	4.1	3.3	4.2	4.4	2.5	2.8	3.0	4.2	4.6
6	5.9	6.7	5.3	4.0	3.3	4.4	4.2	2.4	2.6	1.9	1.5	2.9
8	-1.9	-1.1	0.6	3.2	3.1	4.4	4.0	-0.2	-1.4	-1.9	-2.2	-2.1
10	-3.0	-2.8	-2.4	-1.9	-0.7	0.6	-1.0	-2.2	-2.5	-2.5	-2.9	-3.0
12	-3.7	-3.6	-3.0	-2.5	-1.7	-1.9	-2.2	-1.9	-3.0	-3.1	-3.3	-3.6
14	-3.6	-3.5	-2.9	-2.2	-1.9	-2.1	-2.2	-2.8	-3.0	-3.0	-3.5	-3.6
16	-2.9	-2.7	-2.0	-1.3	-0.9	-1.0	-1.5	-2.2	-2.5	-2.6	-2.8	-2.9
18	-1.6	-0.9	0.7	1.9	1.7	2.7	0.6	-0.9	-1.4	-1.6	-1.8	-1.8
20	2.3	4.2	3.3	3.2	2.8	5.0	3.2	1.2	1.3	1.0	0.3	0.6
22	4.2	5.6	3.7	3.8	3.1	4.9	4.2	2.1	2.1	2.6	3.0	3.8

Source: G.A. DeMarrais, "Vertical Temperature Difference Observed over an Urban Area", Bull. Amer. Meteor. Soc., 42, 1961, Fig. 2, p. 549.

Table 9

Mean Hourly Temperature Gradients in $^{o}C(100m)^{-1}$ for the months of August through July in Rye, Sussex, England. Based on observations from July 1945 to June 1948 (350 ft. - 50 ft.). Curved lines through data indicate sunrise and sunset.

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
0	1.2	1.0	1.6	1.0	0.7	0.3	0.1	1.0	0.9	1.1	1.2	1.0
2	1.3	1.0	1.7	1.2	0.9	0.5	0.1	1.2	1.2	1.2	1.0	1.0
4	1.3	1.1	1.9	1.2	0.7	0.4	0.2	1.1	1.4	1.0	1.0	1.1
6	0.9	1.2	2.0	1.1	0.7	0.2	0.1	1.0	1.2	0.2	0.0	0.2
8	-0.7	-0.1	1.2	1.0	0.7	0.3	0.0	0.1	-0.6	-1.0	-1.0	-0.6
10	-1.0	-0.8	-0.3	0.0	0.4	-0.1	-0.4	-0.9	-1.1	-1.2	-1.2	-0.8
12	-1.2	-0.9	-0.8	-0.4	-0.3	-0.5	-0.9	-1.0	-1.2	-1.2	-1.2	-0.9
14	-1.1	-0.9	-0.7	-0.4	-0.3	-0.5	-0.6	-0.9	-1.1	-1.2	-1.2	-0.9
16	-0.9	-0.8	-0.3	0.1	0.0	-0.2	-0.6	-0.6	-1.0	-1.1	-1.0	-0.6
18	-0.5	-0.2	0.5	0.5	0.3	0.1	-0.2	0.2	-0.4	-0.6	-0.6	-0.3
20	0.4	0.7	1.2	0.7	0.5	0.2	0.0	0.7	0.2	0.4	0.4	0.5
22	0.9	0.8	1.6	0.9	0.6	0.3	0.1	1.0	0.7	0.9	0.9	1.0

Source: G.A. DeMarrais, "Vertical Temperature Difference Observed over an Urban Area", Bull. Amer. Meteor. Soc., 42, 1961, Fig 3, p. 550.

The intensities of the inversions at night and in the early morning were quite comparable. Thus there was no pronounced difference between the Rye and the Edmonton data as one would have expected. A complicating factor lies in the climatic differences between the two sites.

Comparison of Calgary and Idaho Falls, Idaho

In spite of the 20 meters difference in thickness in the two layers these sites have much in common. They both show the features of typical open country sites with superadiabatic conditions prevailing in the daytime and moderate to strong inversions at night. Note that Tables 7 and 8 show that the individual values for the two stations were in close agreement during the day but that the inversions were somewhat stronger in Idaho Falls. Note that Calgary tower is in a valley.

Comparison of Calgary and Rye, Sussex, England

In this case Calgary, more than Rye, (Table 10) showed the typical features of a country station with steeper positive lapse rates in the daytime and also steeper negative lapse rates at night and in the early morning. As in the case of Edmonton this can be explained possibly by differences in climate; Rye to some extent probably being influenced by the sea which would at least reduce the strength of the inversions.

Table 10

Mean Hourly Temperature Gradients in $^{o}C(100m)^{-1}$ for the months of August through July in Rye, Sussex, England. Based on observations from July 1945 to June 1948 (155 ft. - 50 ft.). Curved lines through data indicate sunrise and sunset.

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
0	1.9	1.6	3.1	2.4	1.4	0.5	0.4	1.4	2.1	1.4	1.4	0.9
2	1.9	1.7	3.5	2.6	1.6	0.9	0.4	1.6	2.6	1.9	1.6	1.2
4	2.3	2.1	4.0	2.6	1.4	0.7	0.4	1.7	3.1	1.7	1.6	1.2
6	1.2	2.1	4.0	2.3	1.4	0.4	0.4	1.7	2.3	0.4	-0.4	-0.7
8	-1.6	-0.5	2.1	1.7	1.4	0.5	0.2	0.2	-1.4	-1.7	-1.6	-1.7
10	-2.1	-1.6	-0.5	0.2	0.5	-0.2	-0.9	-1.2	-1.9	-2.1	-2.1	-2.1
12	-2.1	-1.7	-1.2	-0.5	-0.5	-0.9	-1.6	-1.4	-1.6	-1.9	-1.9	-2.1
14	-2.1	-1.7	-1.0	-0.5	-0.4	-0.7	-1.4	-1.2	-1.6	-1.9	-2.3	-2.3
16	-1.6	-1.4	-0.4	0.5	0.2	-0.4	-0.9	-1.0	-1.4	-1.6	-1.6	-1.9
18	-0.9	-0.4	1.0	1.2	0.7	0.2	-0.2	0.2	-0.4	-0.9	-1.0	-1.0
20	0.9	1.2	2.4	1.6	1.0	0.4	0.4	1.2	0.9	0.5	0.7	0.5
22	1.4	1.4	3.3	2.1	1.2	0.7	0.4	1.6	1.4	1.2	1.2	0.9

Source: G.A. DeMarrais, "Vertical Temperature Difference Observed over an Urban Area", Bull. Amer. Meteor. Soc., 42, 1961, Fig.7, p. 553.

CONCLUSIONS

Researchers in the United States have obtained useful estimates of smoke emission rates for different cities by using various statistical techniques. However, the author found that such methods were not applicable to the city of Edmonton. M.E. Miller and G.C. Holzworth found that as much as 70% of the total variation in smoke emission could be explained using mean daily temperature as a predictor for smoke emission rates[1]. This, compared with the author's 0.4%, shows clearly that temperature variations do not account for a significant portion of the variation of smoke output in Edmonton, providing the mathematical model from which the smoke emission rates were obtained is valid. If so, a reasonable explanation for the low predictability is that space heating, which is temperature dependent, is not a major source of smoke, because of the use of natural gas. The slight variation with temperature in smoke output from combustion engines is not enough to be significant. The failure of this approach prompted a test of linear multiple regression using meteorological variables for the prediction of mean daily smoke concentrations. The predictors - mean daily wind speed, mean daily heat island intensity and mean daily vertical temperature gradient - were able to explain 40% of the total variation in mean daily smoke concentrations. Of the three predictors, wind speed and vertical temperature gradient were of equal importance while the horizontal temperature gradient was not a significant predictor. A test with six random samples showed the derived weights on the independent

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[1]M.E. Miller and G.C. Holzworth, An Atmospheric Diffusion Model for Metropolitan Areas. Air Resources Field Research Office, ESSA Cincinnati, Ohio, 1967, p.p. 46 - 50.

variables to be very stable. A second test on an independent data sample showed that the prediction equation was quite stable for daily variations but that it failed to show skill in predicting monthly mean smoke concentrations.

A t-test, using the method of paired samples applied to the Edmonton thermograph data, showed the existence of a significant change in temperature as one approached the center of the city from the outskirts. This difference was attributed to differences in heat-storage capacity, differences between incoming and outgoing radiation because of pollution, and the excess heat due to activities in the city. The urban heat island was divided into at least two parts by the river valley. The results obtained from the thermograph data were supplemented in a few instances by horizontal temperature traverses.

Analysis of the vertical temperature distribution in Edmonton revealed that near-adiabatic conditions prevailed during the daylight hours in the summer; and isothermal, or weak positive or negative lapse prevailed throughout the rest of the year. Temperature inversions of moderate strengths occurred throughout the year at night and in the early morning hours.

The same analysis applied to Calgary showed that adiabatic to superadiabatic conditions prevailed during the daylight hours throughout the seven months that were studied. Moderate to strong inversions occurred throughout these months at night and in the early morning hours. The results of the vertical temperature distribution from Edmonton and Calgary were compared with similar results from other sites and showed that Edmonton, more so than Calgary, represented the typical city

situation. A possible explanation for this difference may be the peripheral location of the Calgary instrument tower.

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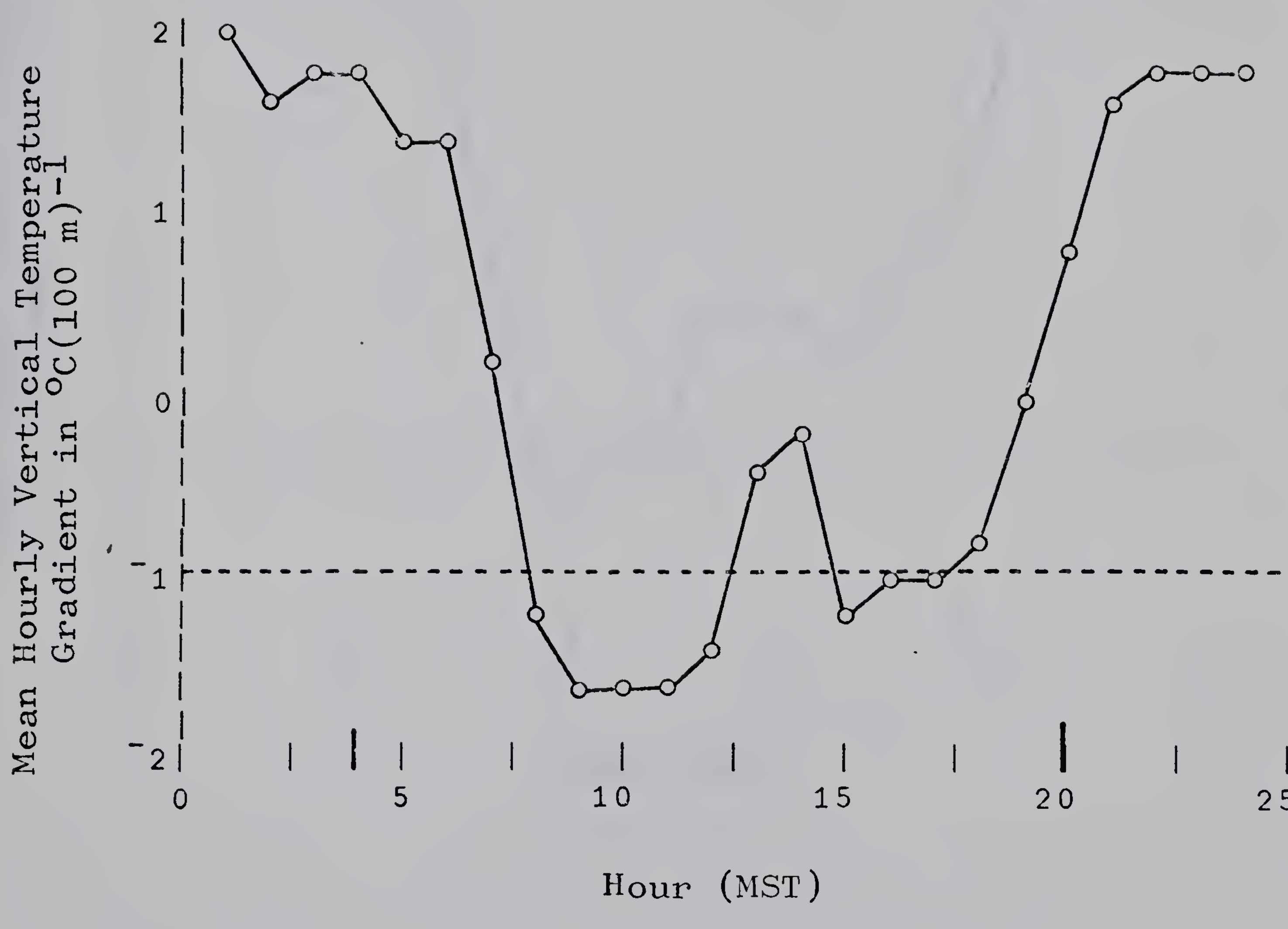
APPENDIX I

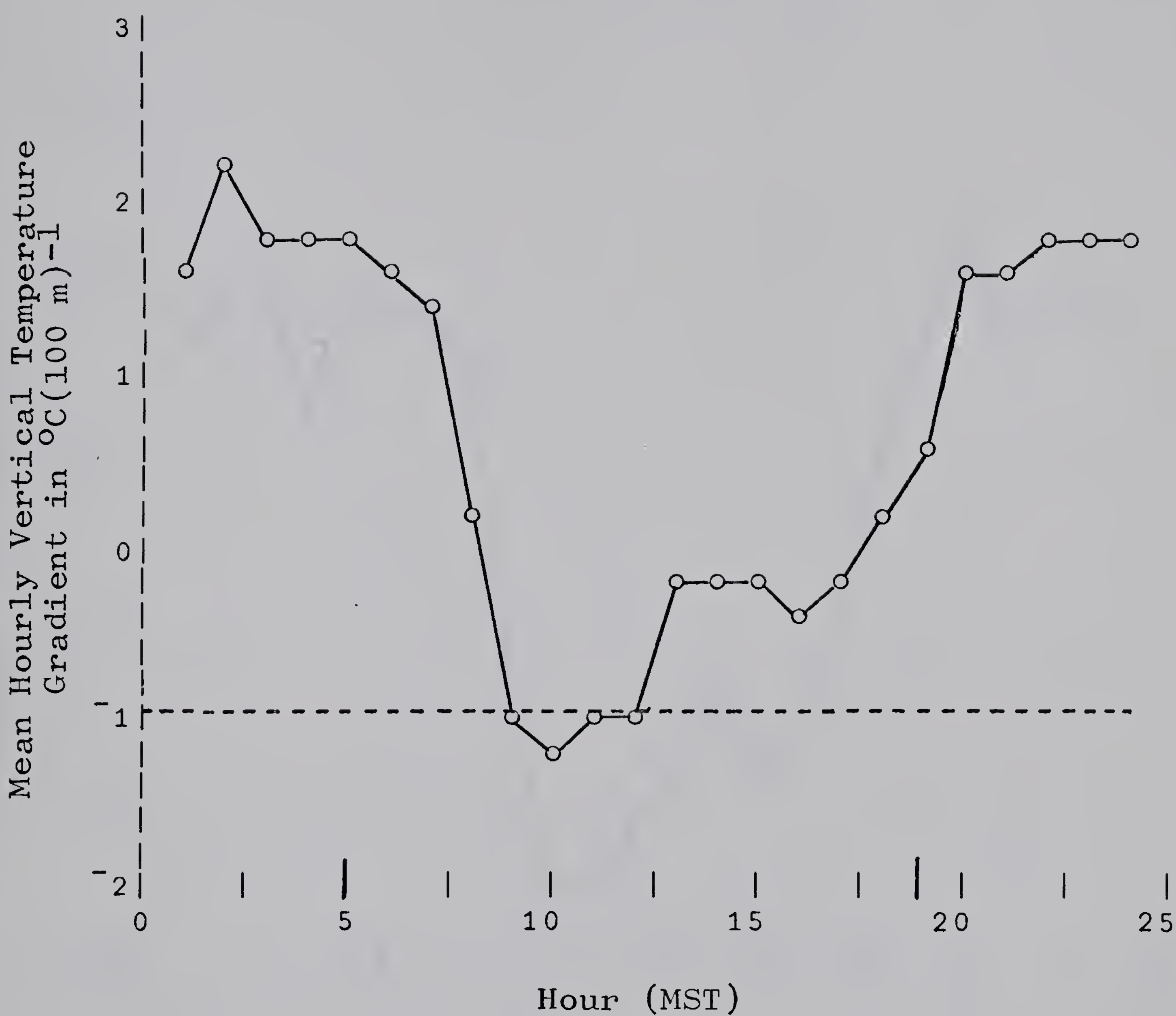
Graphs of the hourly vertical temperature gradient in $^{o}C(100\ m.)^{-1}$ between 15 m. and 113 m. on the CN Tower in central Edmonton. Horizontal dashed line marks the dry adiabatic lapse rate. Vertical bars on the abscissa mark the times of sunrise and sunset.

August 1967

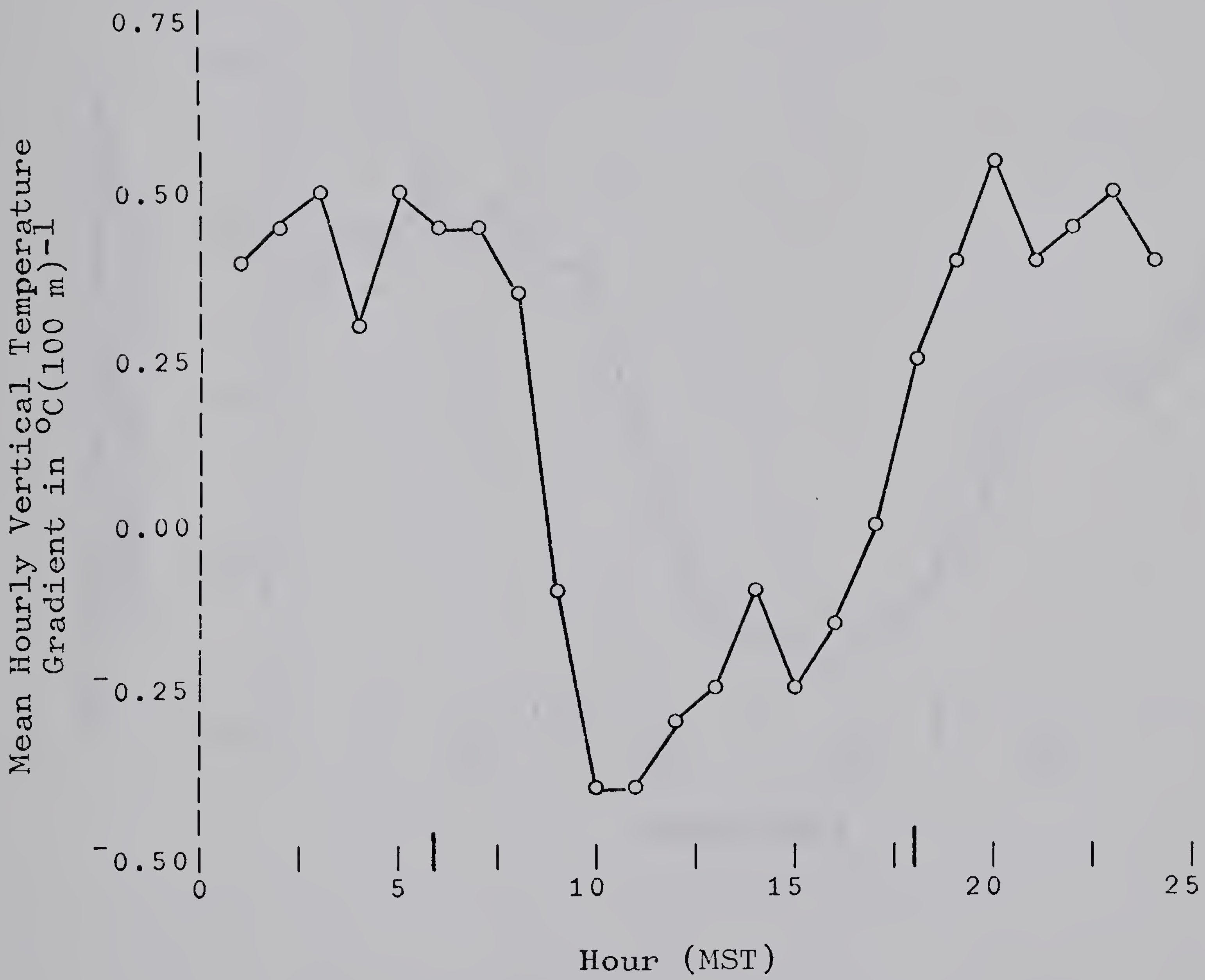


Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
2
1
0
-1
-2
0
5
10
15
20
25
Hour (MST)

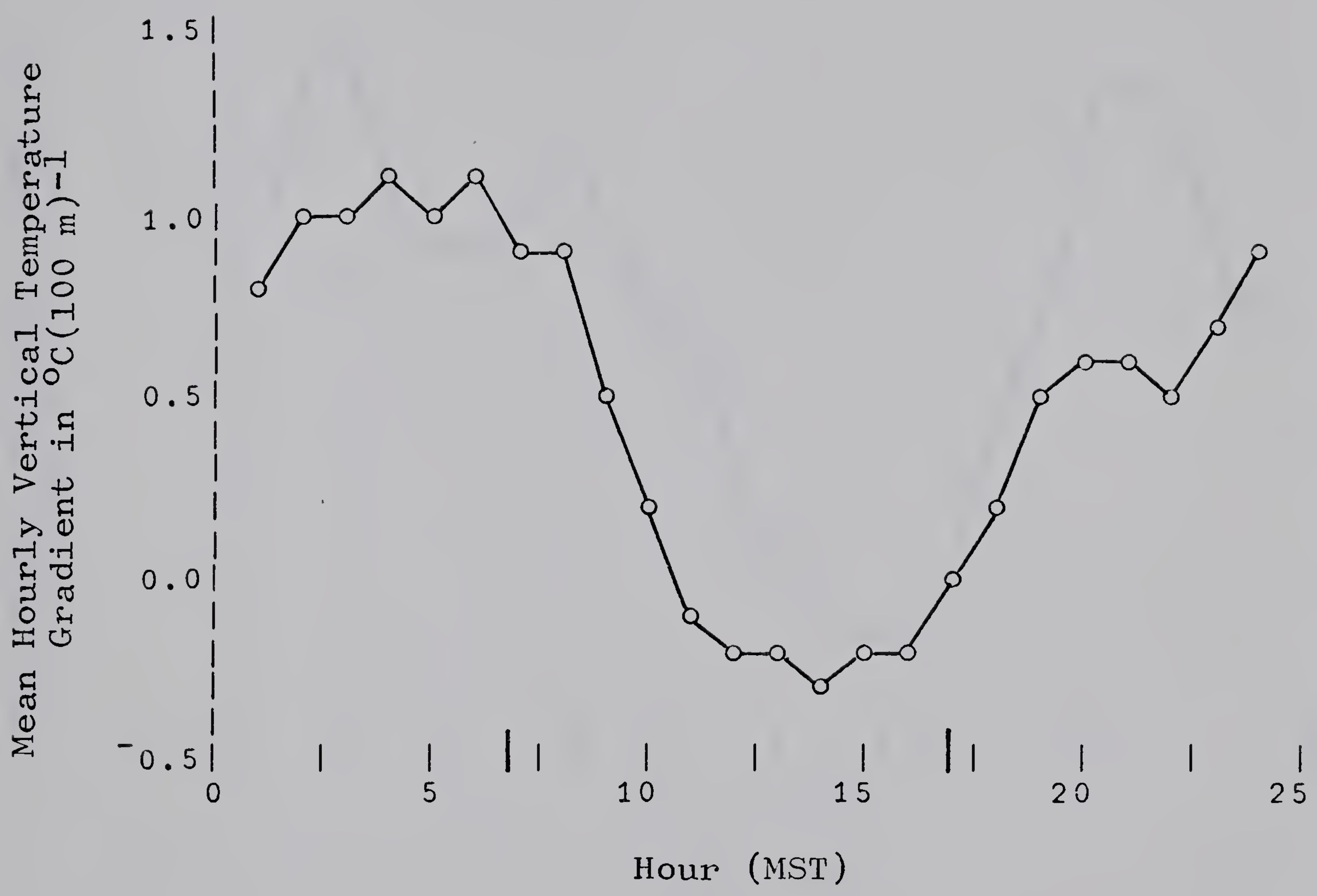
September 1967



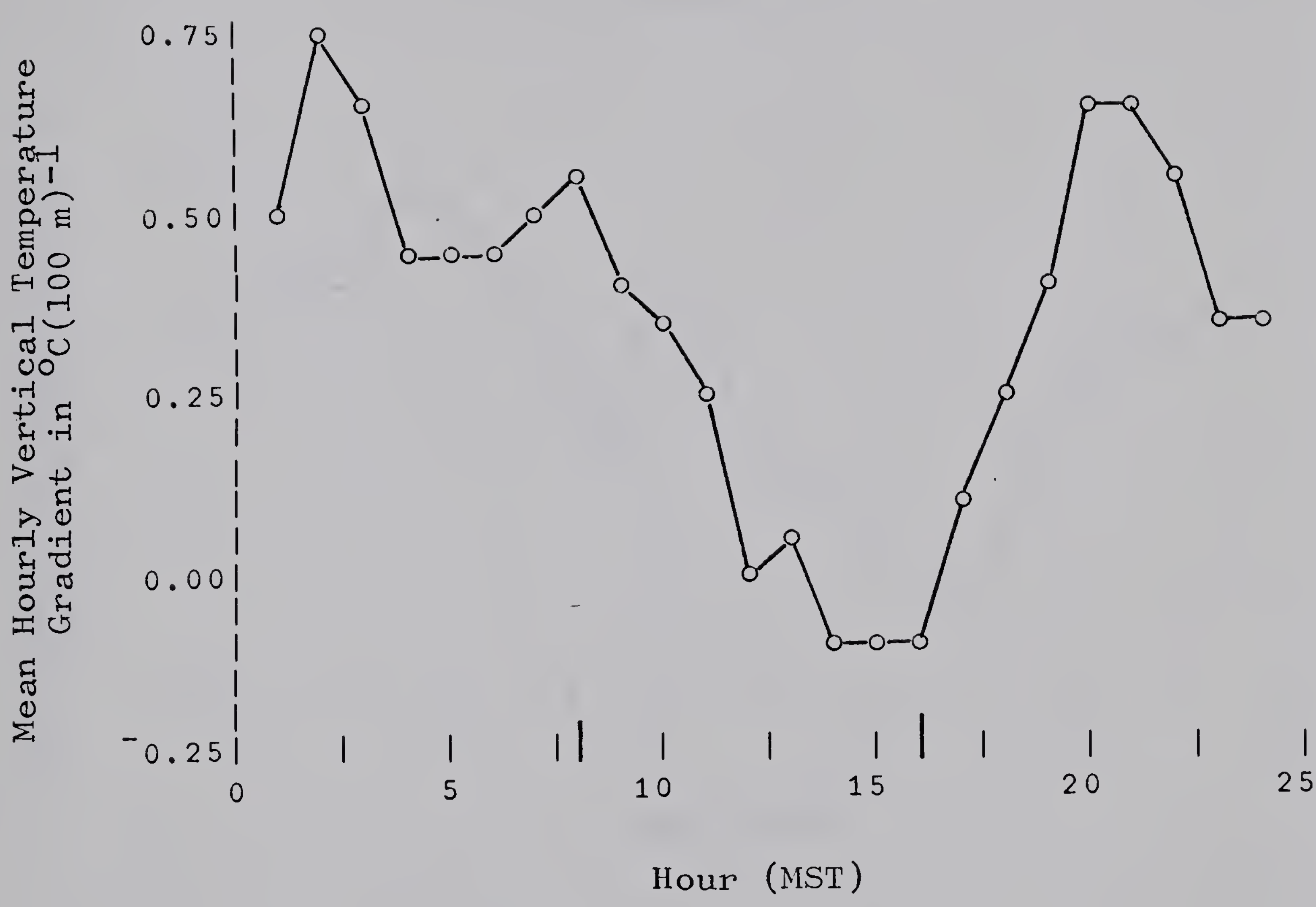
October 1967



November 1967



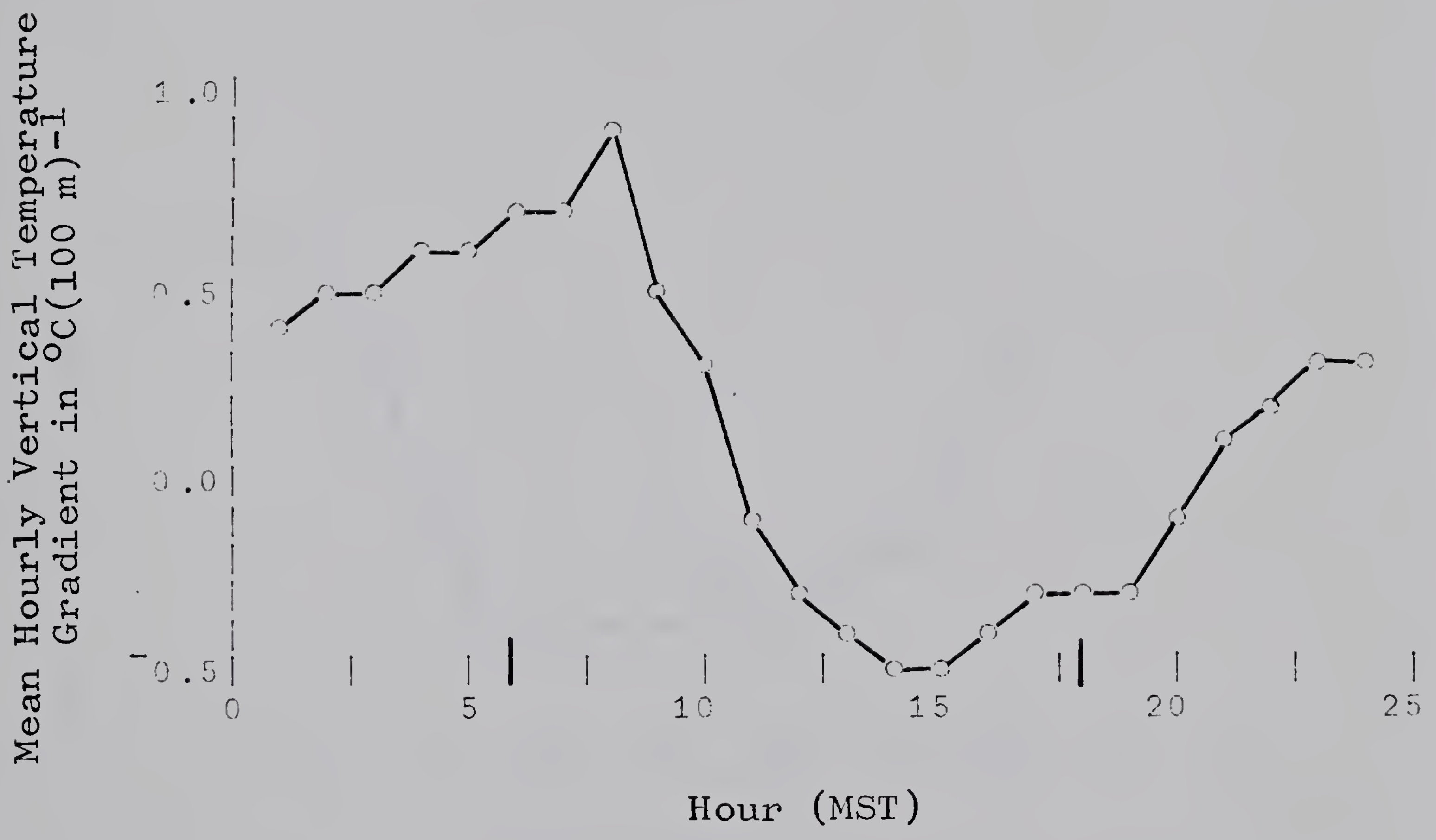
December 1967



January 1968

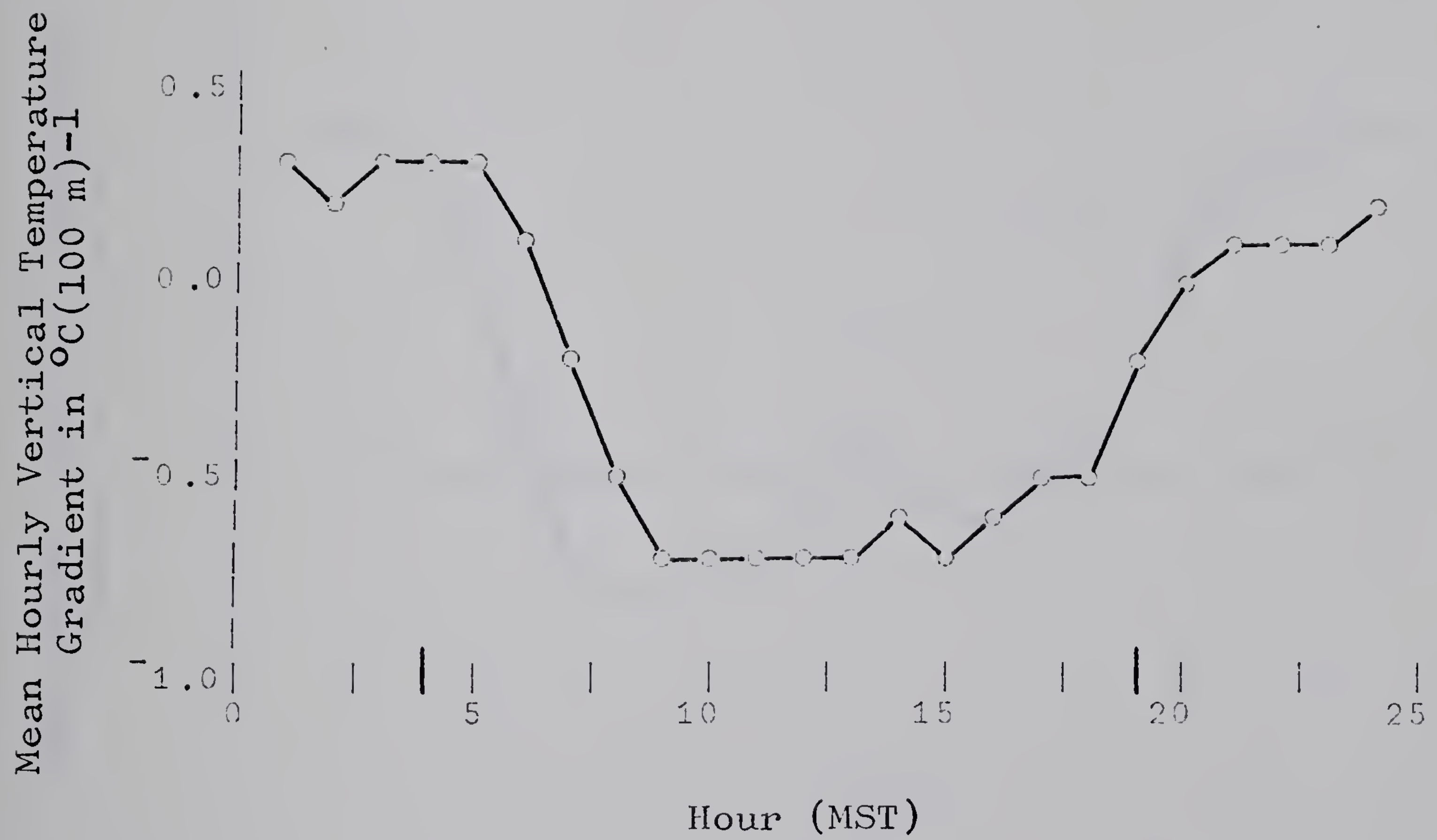
February 1968

March 1968



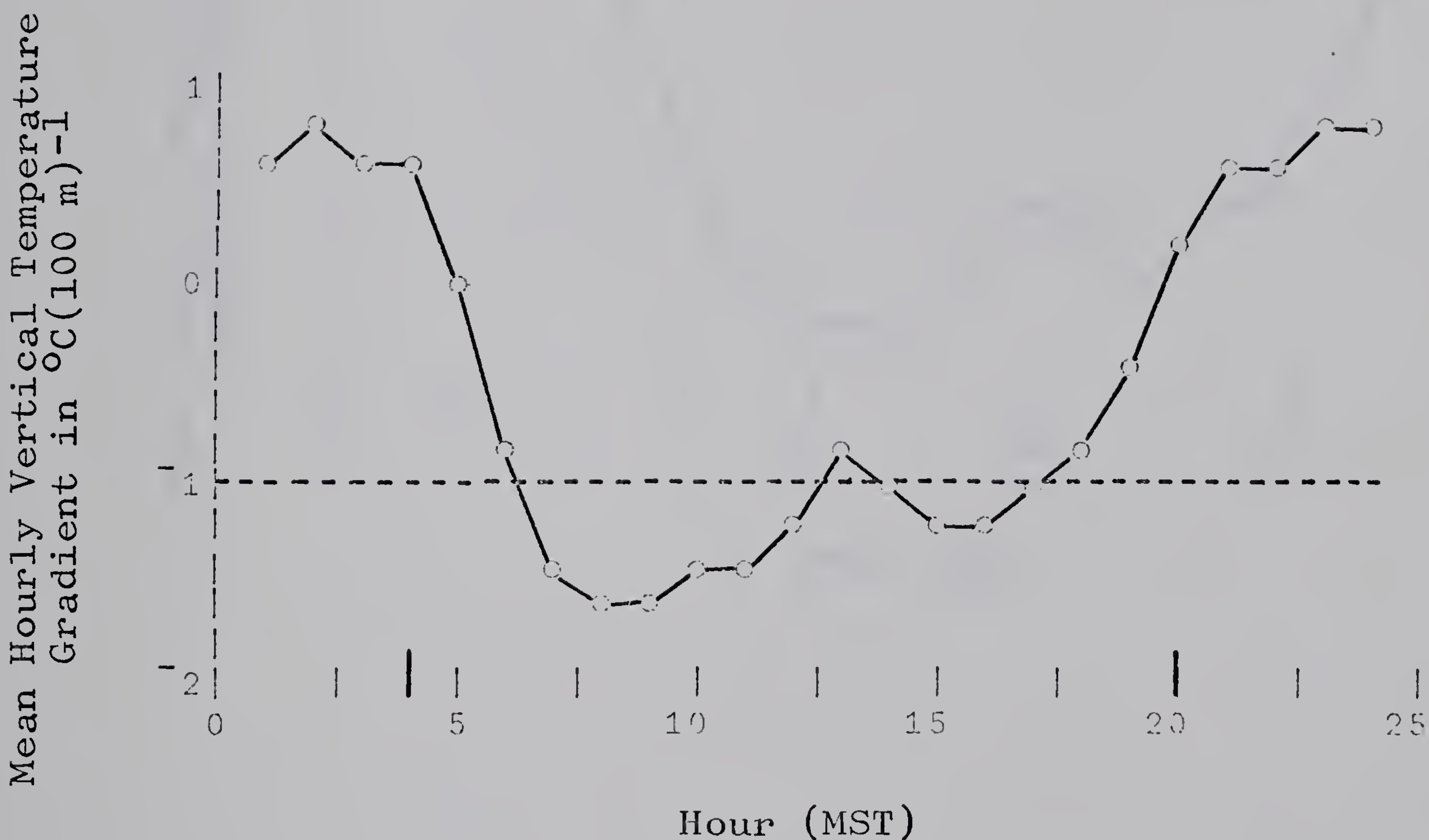
Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
1.0
0.5
0.0
-0.5
0
5
10
15
20
25
Hour (MST)

April 1968



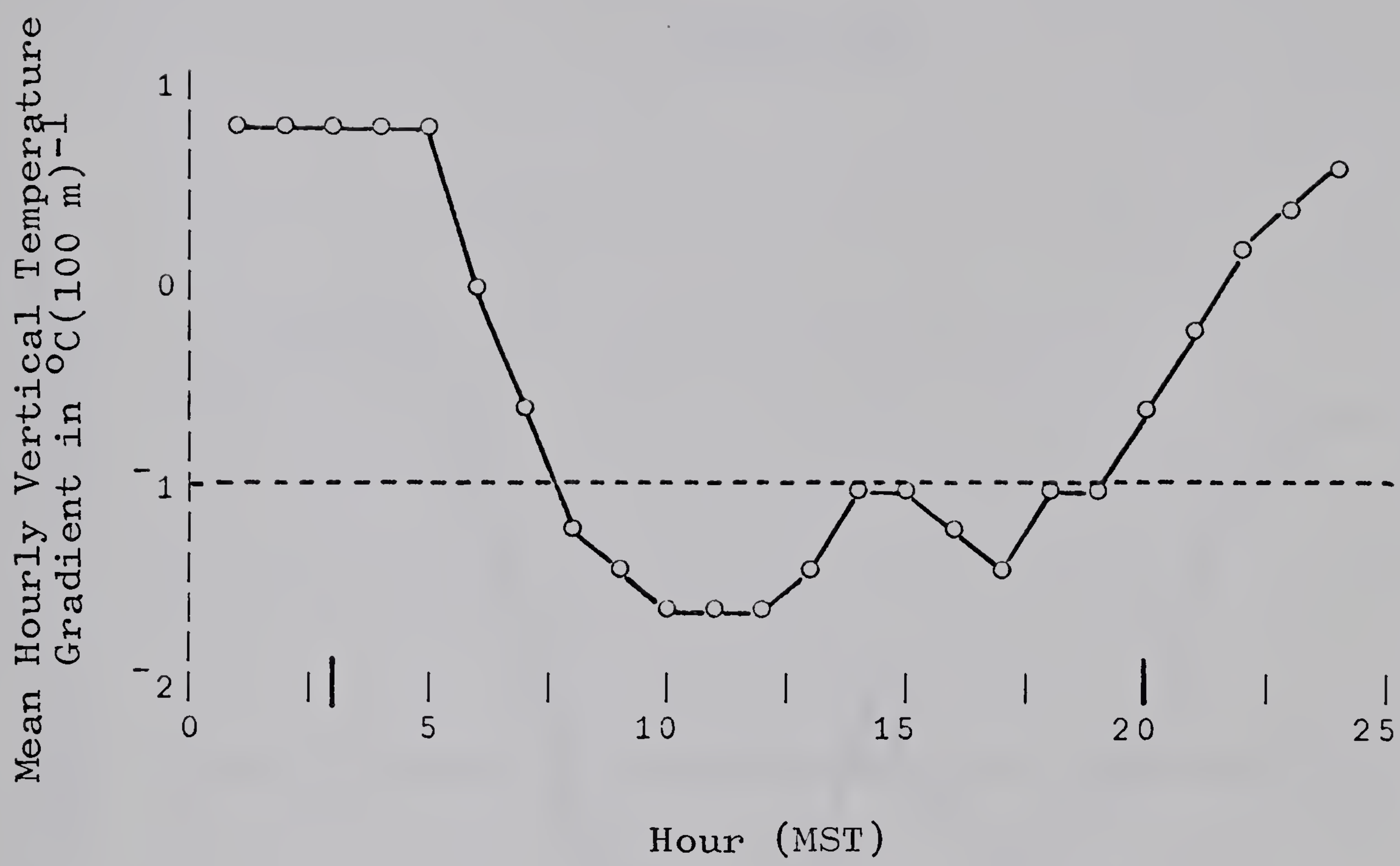
Mean Hourly Vertical Temperature
Gradient in $^{o}C(100\ m)^{-1}$
0.5
0.0
-0.5
-1.0
0
5
10
15
20
25
Hour (MST)

May 1968



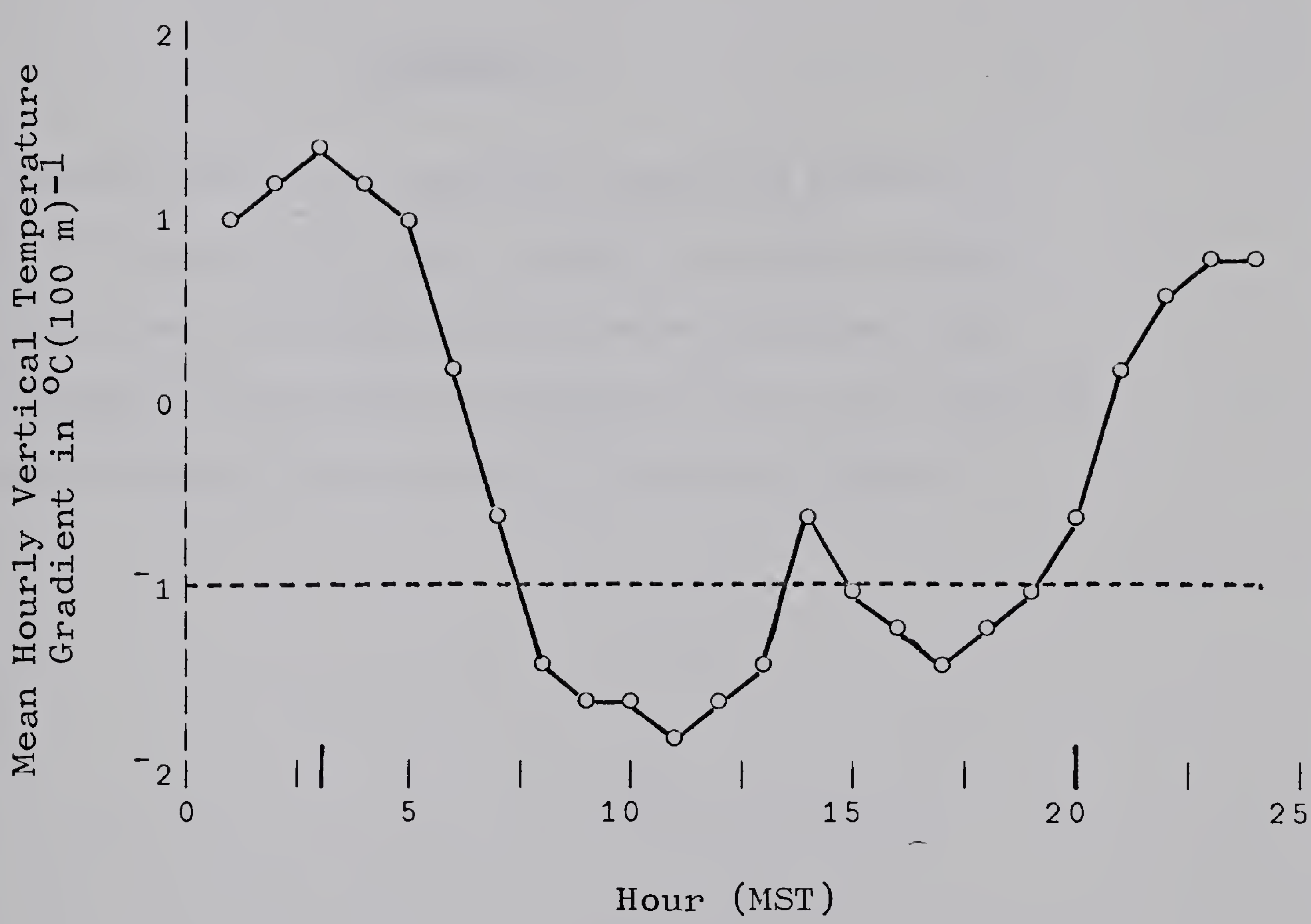
Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
1
0
-1
-2
0
5
10
15
20
25
Hour (MST)

June 1968



Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
1
0
-1
-2
0
5
10
15
20
25
Hour (MST)

July 1968

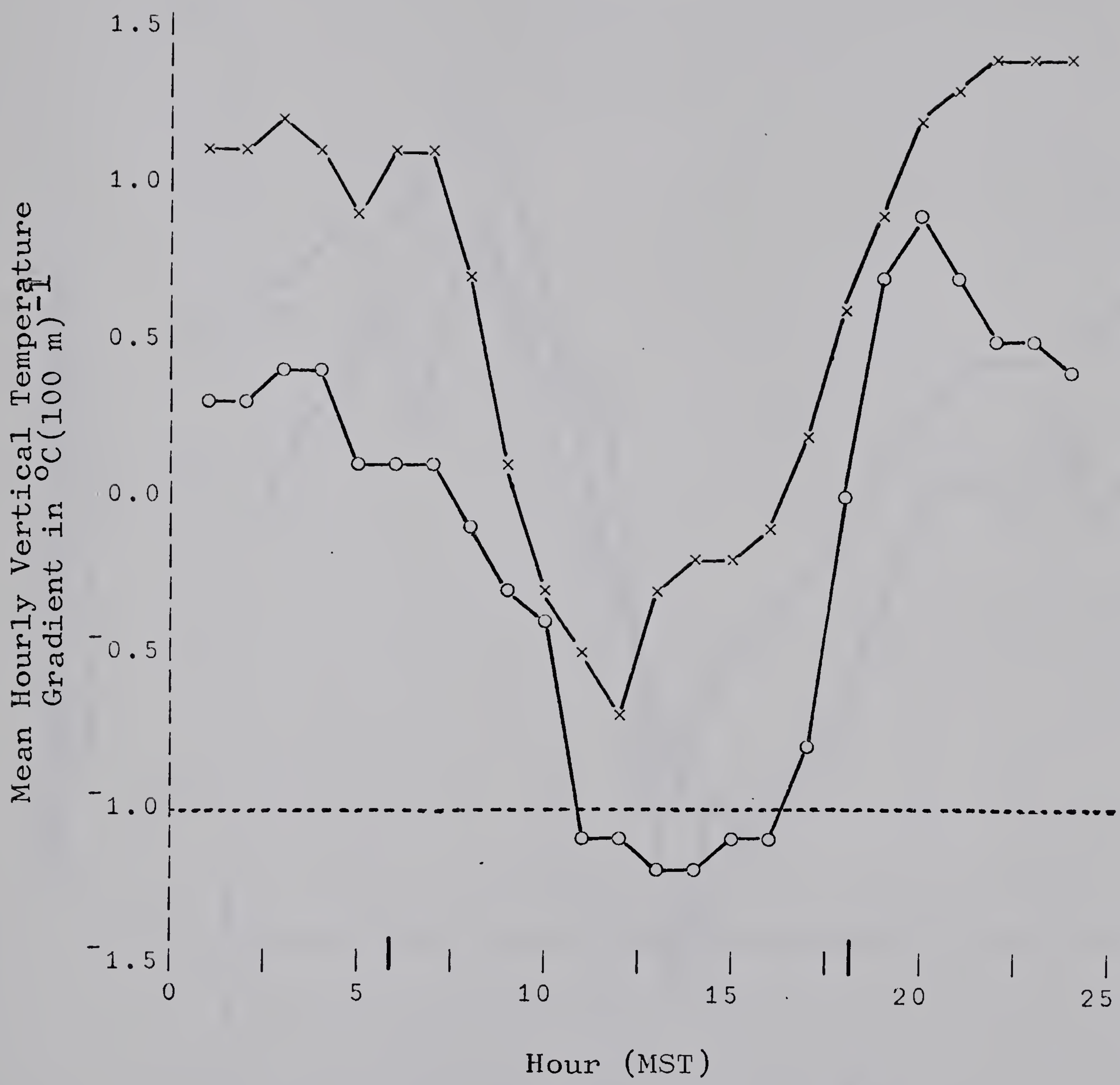


Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
2
1
0
-1
-2
0
5
10
15
20
25
Hour (MST)

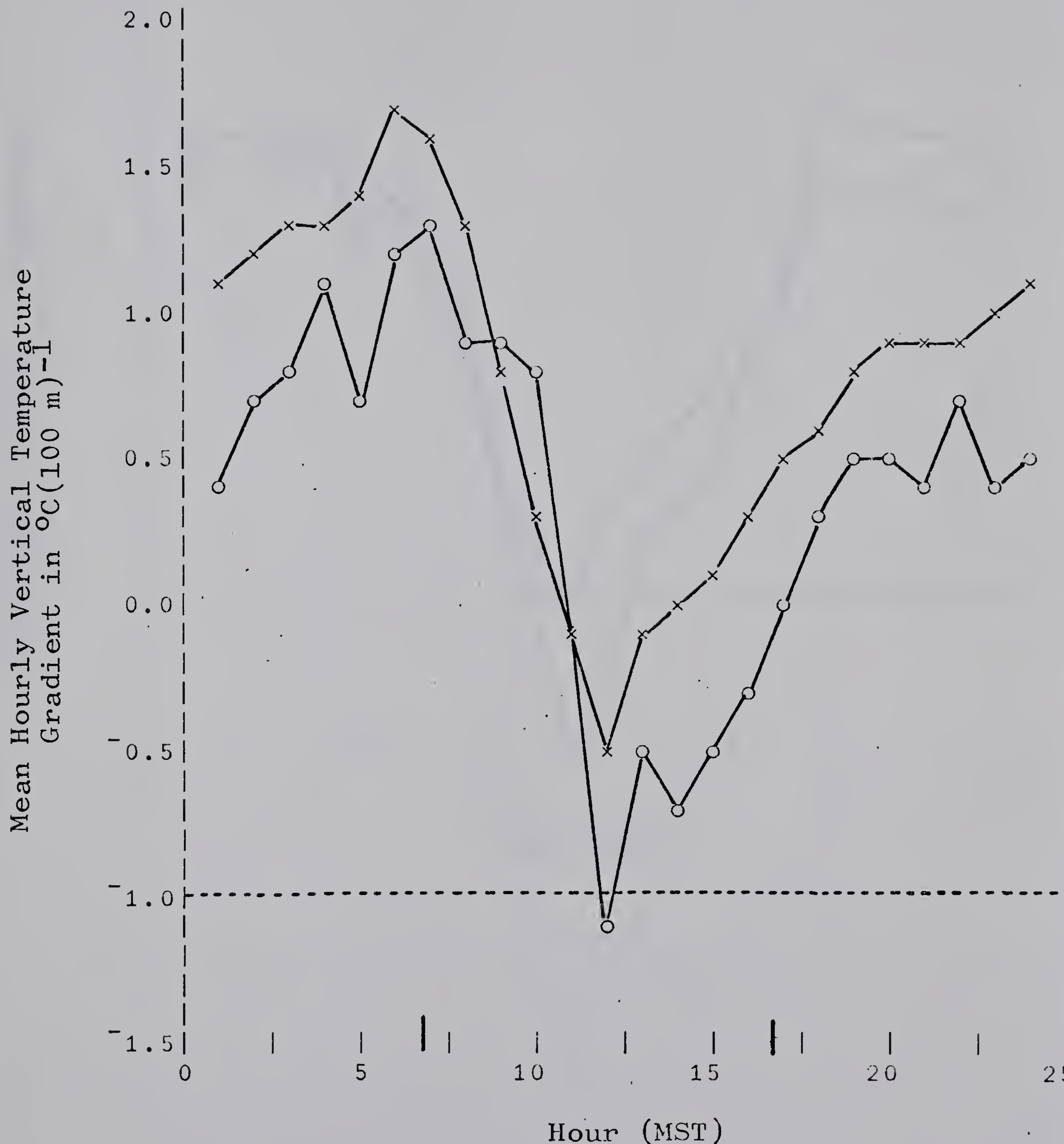
APPENDIX II

Graphs of the hourly vertical temperature gradient in $^{o}C(100\ m.)^{-1}$ for the layers 15 m. to 113 m. (crosses) and 15 m. to 42 m. (circles) on the CN Tower in central Edmonton. Horizontal dashed line marks the dry adiabatic lapse rate. Vertical bars on the abscissa mark the times of sunrise and sunset.

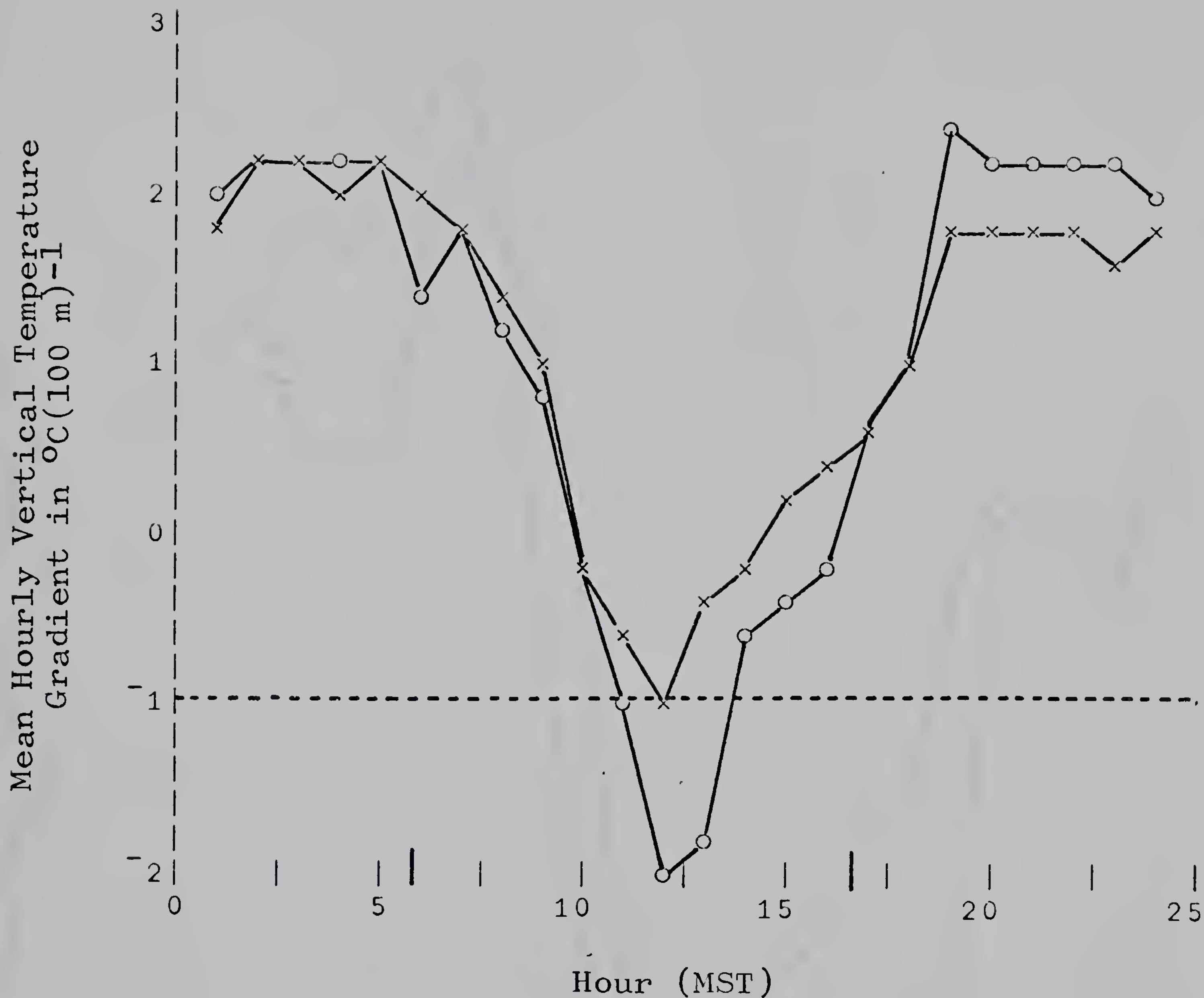
October 1968



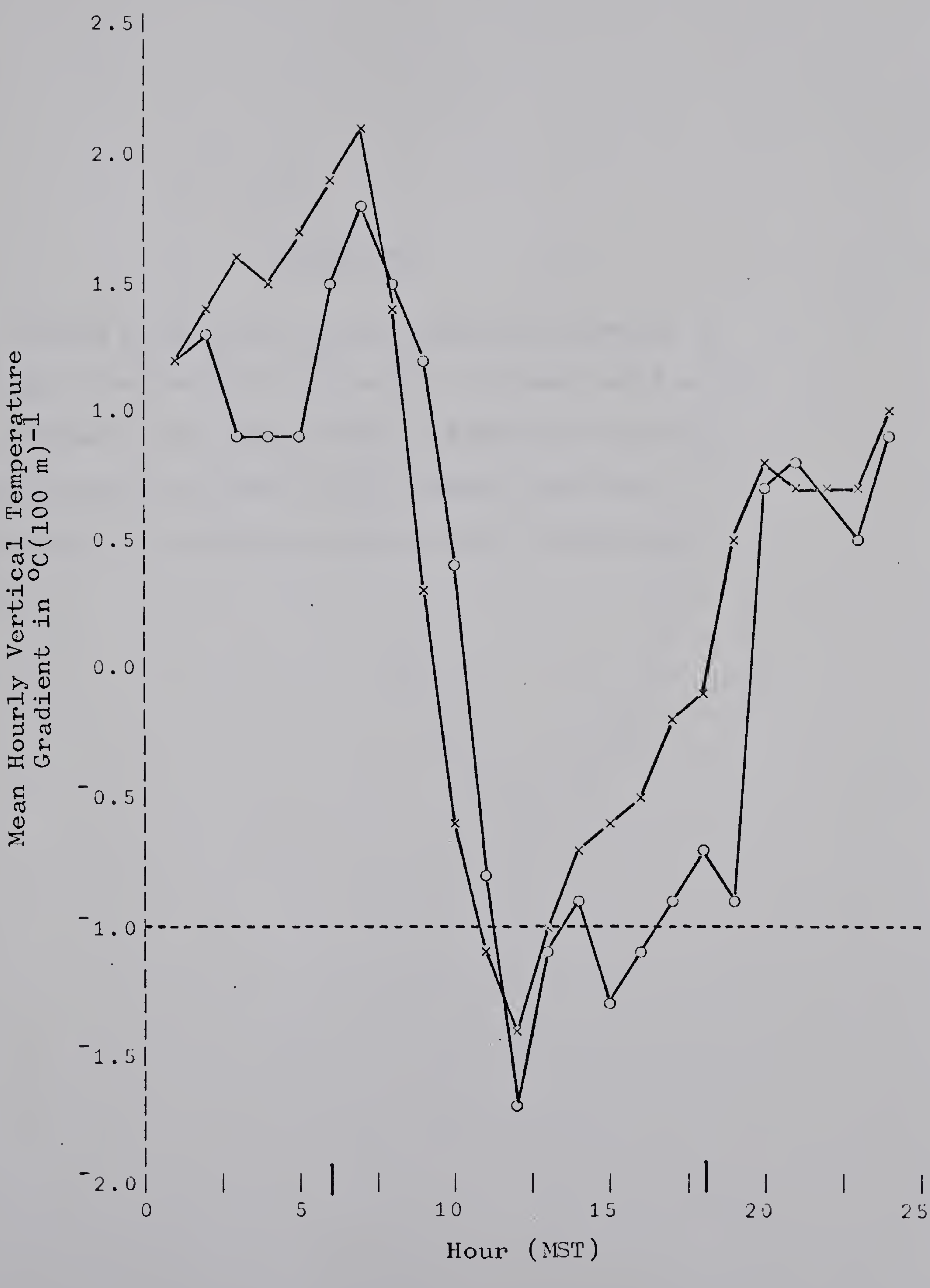
November 1968



February 1969



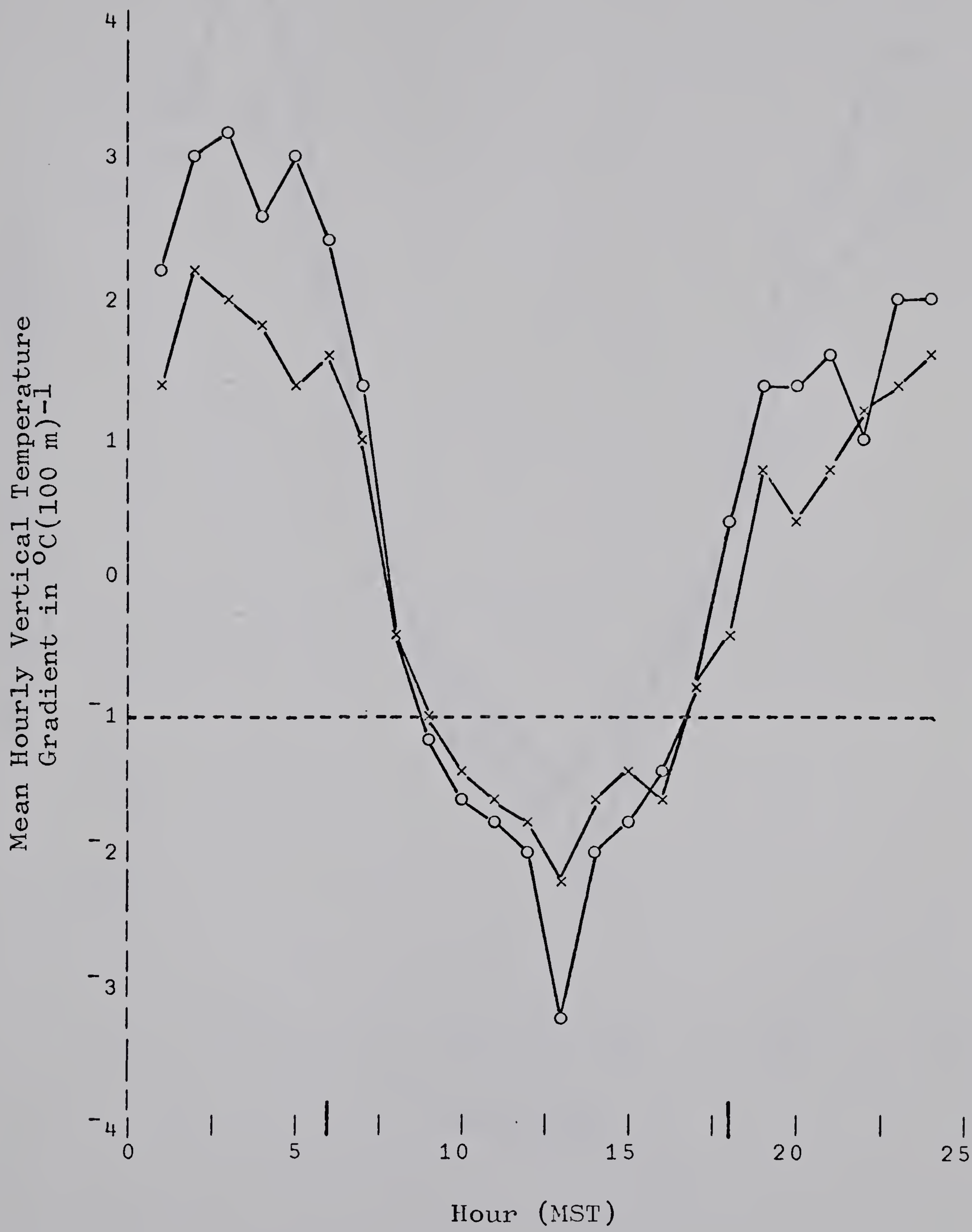
March 1969


2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Mean Hourly Vertical Temperature
Gradient in °C(100 m)-1
0
5
10
15
20
25
Hour (MST)

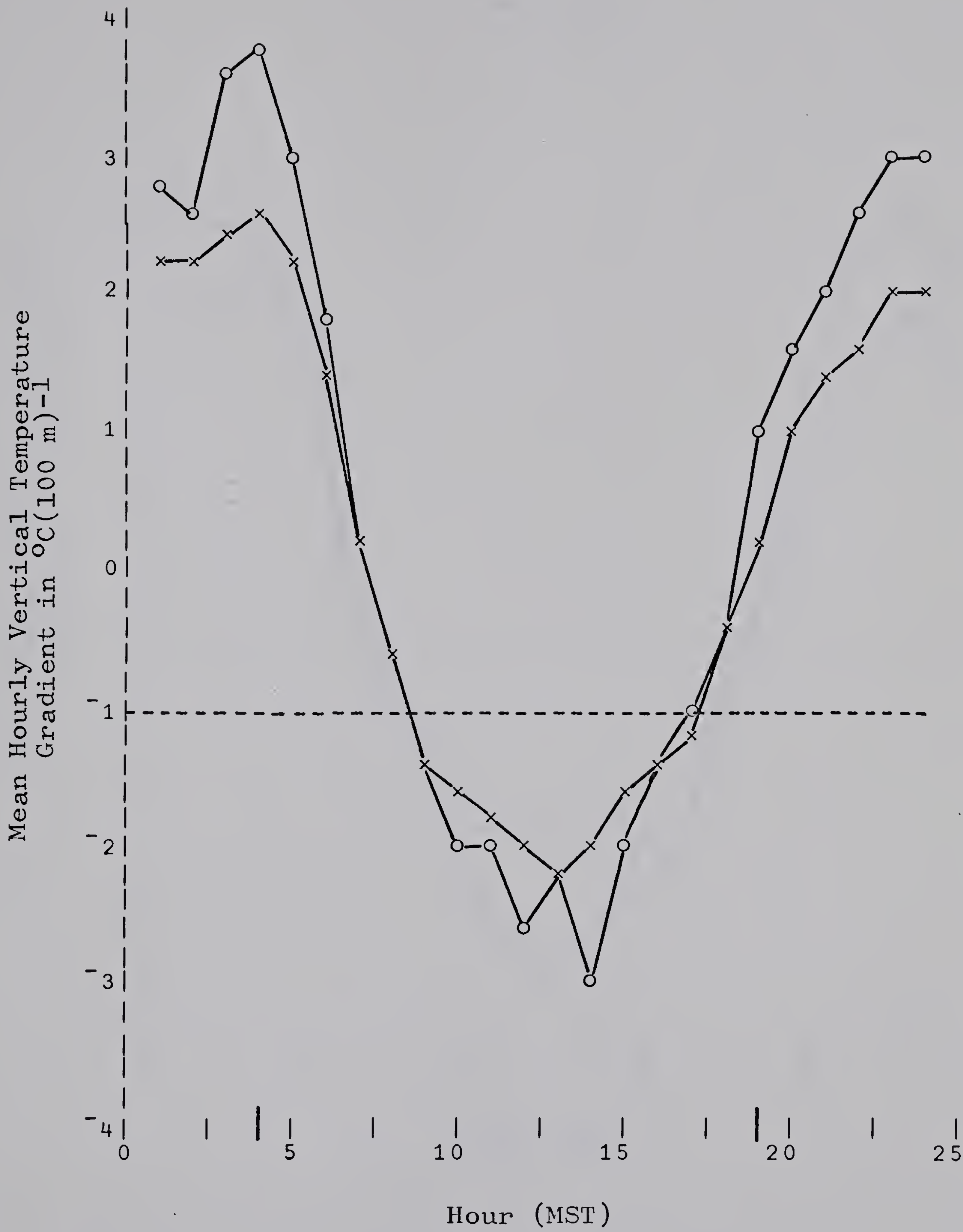
APPENDIX III

Graphs of the hourly vertical temperature gradient in $^{o}C(100\ m.)^{-1}$ for the layers 3 m. to 61 m. (crosses) and 3 m. to 31 m. (circles) on the Calgary Tower in Southeastern Calgary. Horizontal dashed line marks the dry adiabatic lapse rate. Vertical bars on the abscissa mark the times of sunrise and sunset.

March 1968

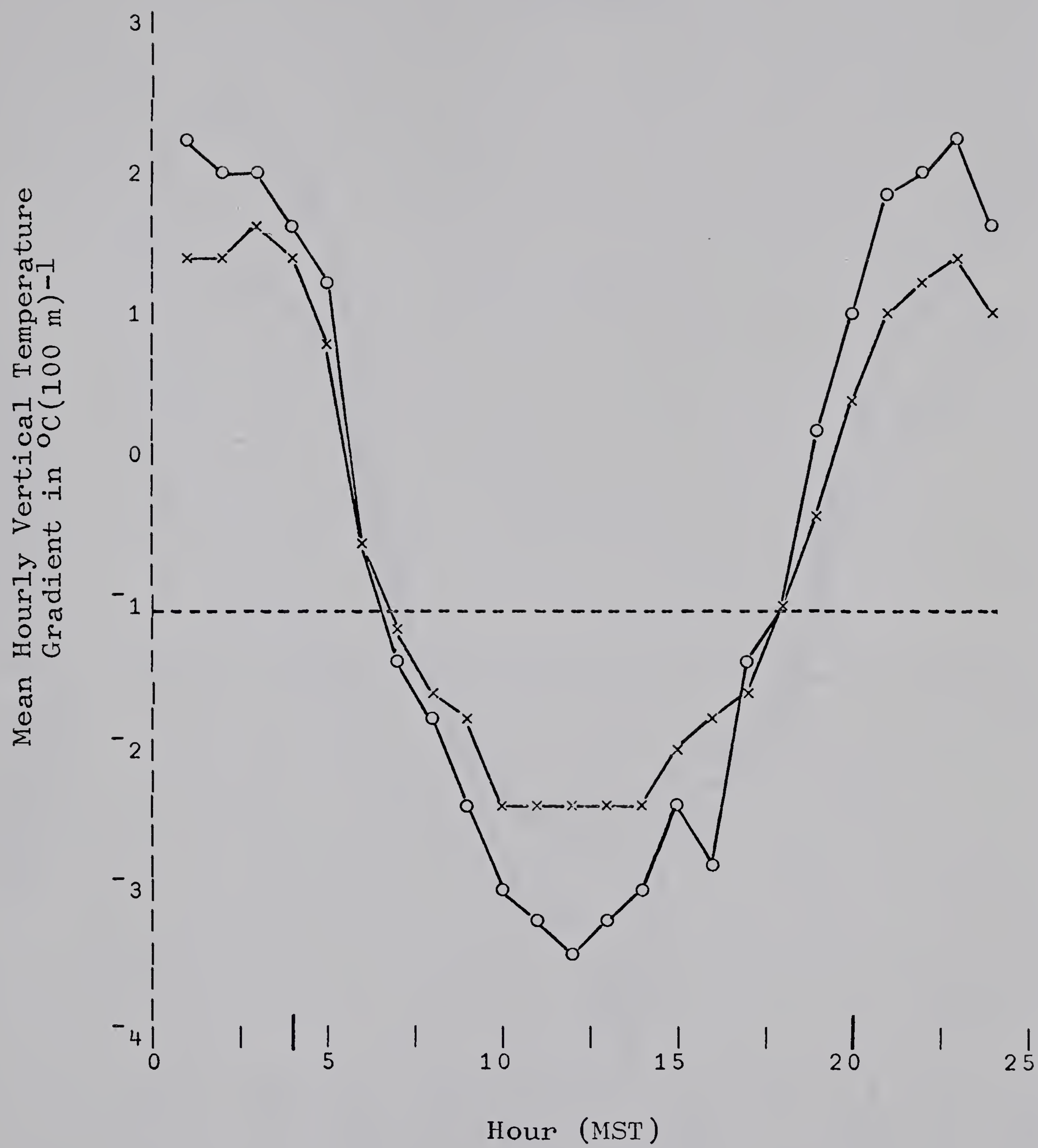

Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
4
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
Hour (MST)

April 1968



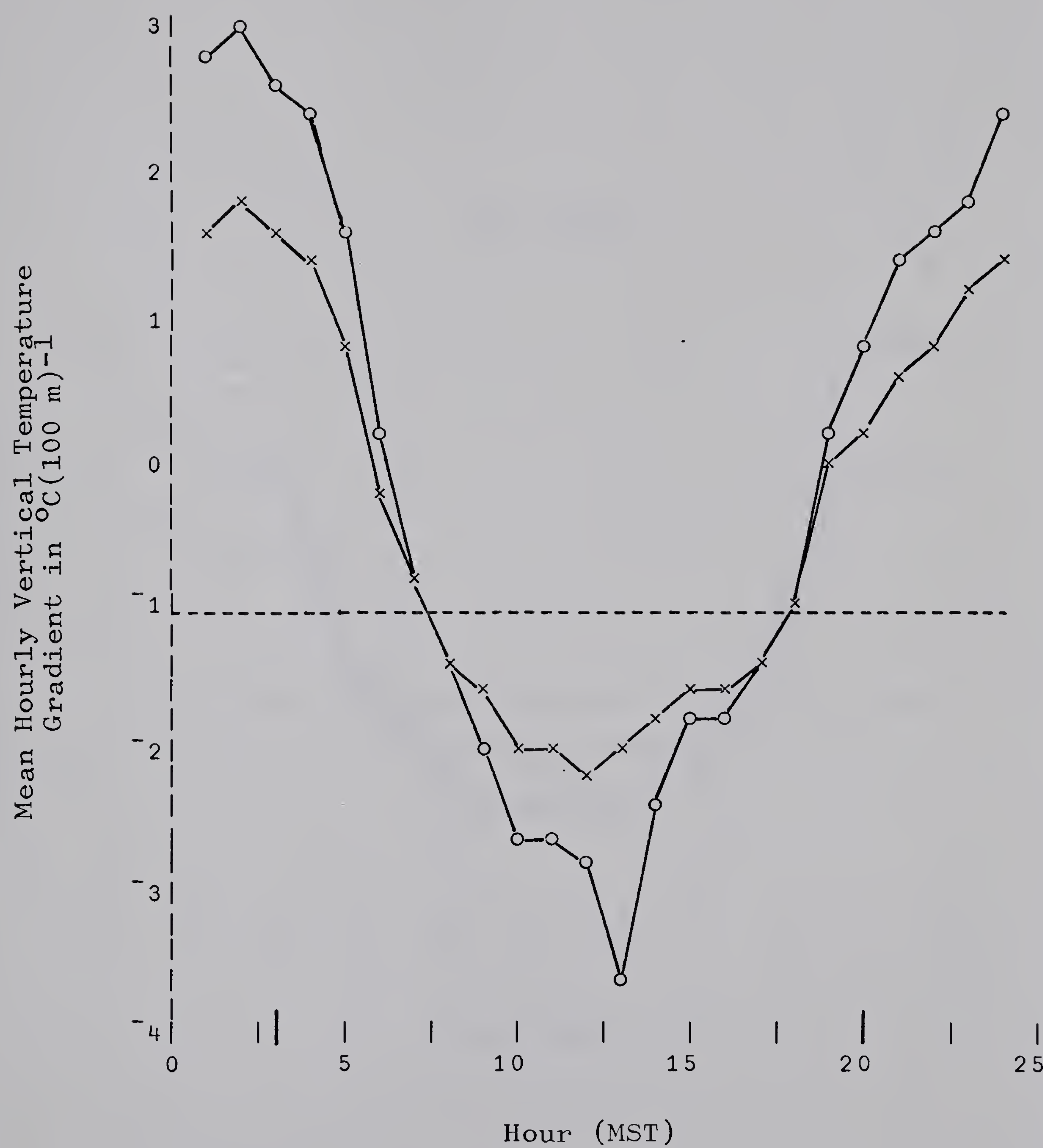
Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
4
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
Hour (MST)

May 1968



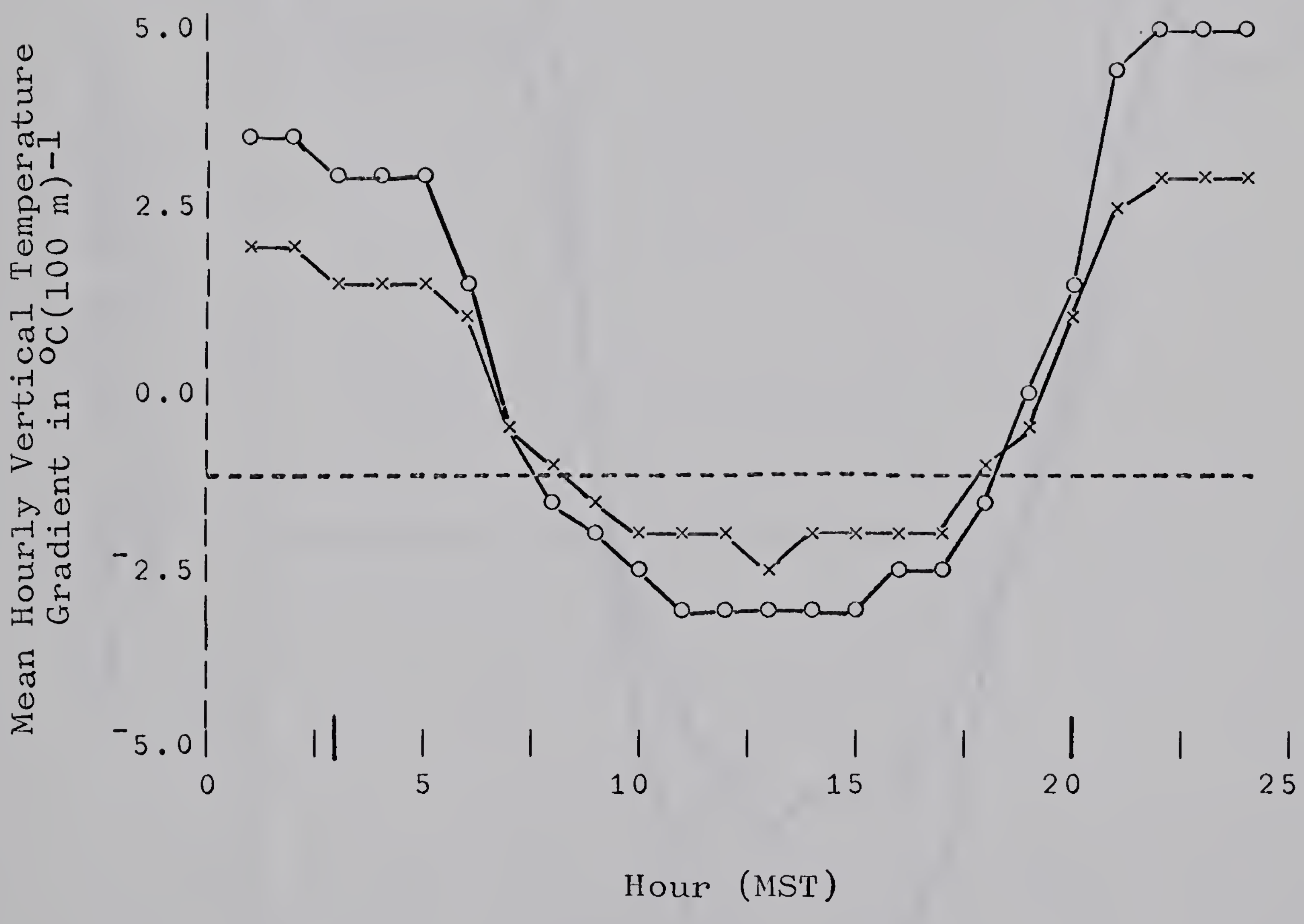
Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
Hour (MST)

June 1968



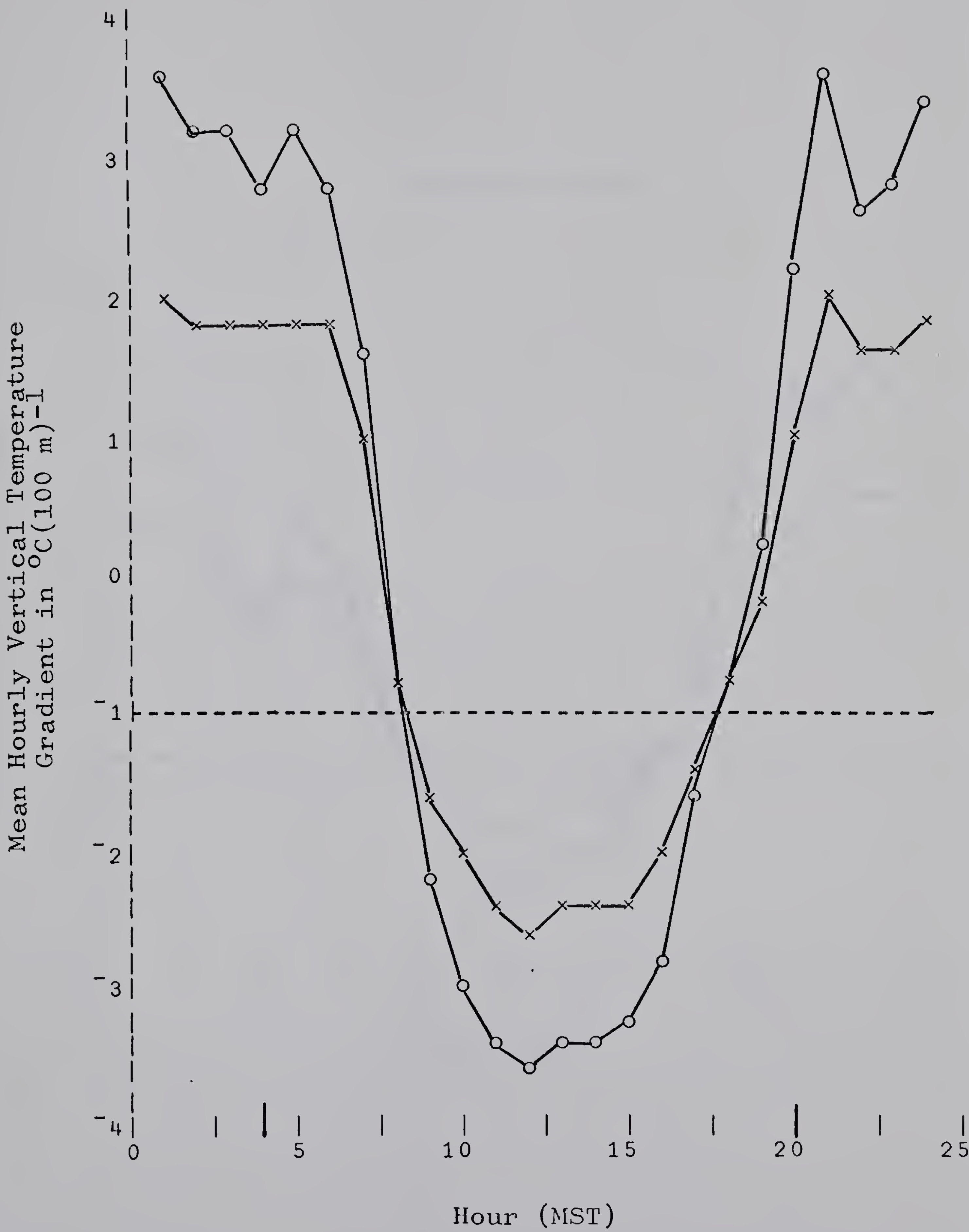
Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
Hour (MST)

July 1968

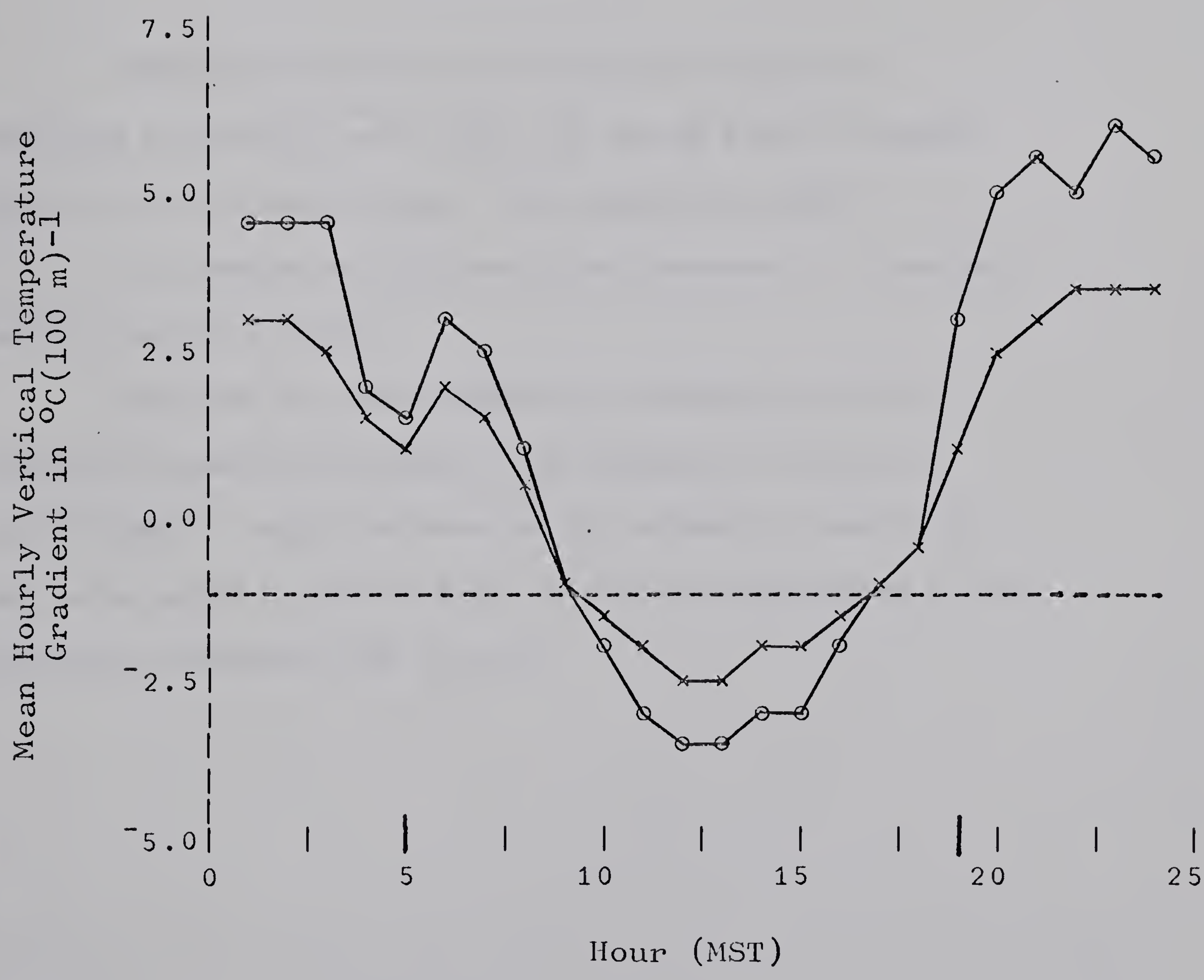


Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
5.0
2.5
0.0
-2.5
-5.0
0
5
10
15
20
25
Hour (MST)

August 1968


Mean Hourly Vertical Temperature Gradient in °C(100 m)-1
4
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
Hour (MST)

September 1968



APPENDIX IV a

Frequency distributions of vertical temperature gradients between 15 m. and 113 m. on the CN Tower in central Edmonton for the months August 1967 through July 1968.

All temperature differences are converted to a standard height interval of 100 m.

Note that the typed numbers are frequencies for 1°C temperature-gradient intervals. The frequencies listed for $-0.99°C(100m)^{-1}$, which indicate the dry adiabatic lapse rate, have to be added to the row below to give the frequencies in the temperature interval -0.99 to 0.01.

August 1967

ΔT_2

Temp. Grad. $^oC(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals	
-9.99																										
-8.99																										
-7.99																										
-6.99																										
-5.99																										
-4.99																										
-3.99																										
-2.99									4	3	4														11	
-1.99								6	5	5	4	5			4	2	3	1							35	
-0.99							2	9	7	10	10	11	3	3	13	11	11	7	2					1	100	
							1	1	1	1	3	3	2	2	3	4	3		1						25)	204
0.01	2	2	3	5	4	6	10	10	10	8	6	8	16	13	7	10	10	17	15	6	4	2	3	2	179)	
1.01	6	10	7	5	7	4	10	1					6	9				2	6	10	2	5	5	7	102	
2.01	7	6	6	6	6	9	3												2	9	13	13	7	4	91	
3.01	3	4	5	4	6	5	1												1	1	3	1	9	5	48	
4.01	6	3	3	3	4	3														1	4	5	2	6	40	
5.01	2	1	2	2																	1	1		2	11	
6.01	1	1	1	2																			1		6	
7.01																										
8.01																										
9.01																										
10.00																										
																									648	

September 1967

ΔT_2

Hour (MST)

Temp. Grad. $^{\circ}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
									1	2															3
-2.99																									
									3	3	4	2													12
-1.99																									
	1					1		3	6	6	8	7	1	2	3	5	2		1						46
-0.99								2	1	3		3		2	1	4	2								18)243
	1	3	5	6	6	4	6	12	15	13	15	14	20	16	16	10	18	16	8	3	4	5	5	4	225)
0.01																									
	10	6	8	8	5	9	8	5	1	1	1	2	6	6	5	7	5	7	7	8	10	4	5	8	142
1.01																									
	8	8	6	3	7	6	7	2	1				1	1	3	2	1	5	9	8	3	7	9	6	103
2.01																									
	3	4	4	3	5	1	2	3						1					2	5	4	6	2	3	48
3.01																									
	2	1		3		2	3												1	3	5	4	4	4	32
4.01																									
	2	2	2	2	2	3		1												1	2	1	3	1	22
5.01																									
	1	3	1	3	1	2	2															1		2	16
6.01																									
		1	2		1																				4
7.01																									
					1																				1
8.01																									
9.01																									
10.00																									
																									672

October 1967

ΔT_2

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
-1.99																									
	1							2	5	5	3	1		1	1										19
-0.99	1									2	2	1		1	1										8) 367
	14	16	13	12	8	9	11	14	18	18	22	23	26	17	20	23	18	11	9	8	9	12	12	16	359)
0.01																									
	10	8	12	15	18	16	13	9	5	5	4	4	4	11	9	8	12	17	19	16	17	14	14	9	269
1.01																									
	3	4	3	4	3	3	6	2	2			2	1	1			1	1	2	6	4	3	3	3	57
2.01																									
	1	3	2		1	2	1	2		1								1	1	1	1	2	1	1	21
3.01																									
					1	1		2										1						1	6
4.01																									
	1		1						1														1	1	5
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									744

November 1967

ΔT_2

Hour (MST)

Temp. Grad. °C(100m)$^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
-1.99																									
			1							3	2				1				1	1	1		1		11
-0.99			1		1				1	1	2	1													7) 334
	11	10	10	9	7	8	11	11	15	14	16	21	23	24	21	21	17	11	10	11	11	12	13	9	327)
0.01																									
	12	12	9	10	9	10	8	7	5	6	8	6	5	6	7	8	12	14	14	12	10	9	7	11	217
1.01																									
	3	2	2	6	9	4	4	5	3	3	1	2	2		1	1	1	5	5	3	5	5	4	2	78
2.01																									
	1	3	4	1		4	4	2	5	2	1									1	1	1	4	3	37
3.01																									
				1	1	2	2	4	1										1	1	1	1	1	2	18
4.01																									
	1		1		1	1	1	1		1										1	1	1		1	11
5.01																									
	2	1	1	2	2	1																			9
6.01																									
		1		1																				1	3
7.01																									
		1																							1
8.01																									
			1																						1
9.01																									
10.00																									
																									720

December 1967

ΔT_2

Hour (MST)

Temp. Grad. $^{\circ}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
-1.99																									
	1	1	1	1			1	1	1	2	1	4	2	2	1	2	1	2	3		1	2	2	1	33
-0.99				1				1	1	2	1	3	2	2	1	2	1	2	3			1	1		24) 351
	14	14	13	13	13	13	12	12	13	12	14	10	13	15	18	14	15	15	13	17	14	11	13	16	327)
0.01																									
	7	6	8	9	12	11	12	12	9	8	8	12	11	10	9	12	10	8	4	5	5	7	4	4	203
1.01																									
	4	7	6	3	3	5	2	1	4	5	6	2	3	2	2	1	2	2	4	4	5	2	9	6	90
2.01																									
	4	2		3	2			2	2	1	1						2	1	1	3	3	4	2	4	37
3.01																									
	1		2			2	4	1		1									2	1	3	3			20
4.01																									
									1													1			2
5.01																									
								1																	1
6.01																									
					1													1	1						3
7.01																									
			1	1																1					3
8.01																									
9.01																									
	1																								1
10.00																									
																									744

January 1968

ΔT_2

Hour (MST)

Temp. Grad. °C(100m)$^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
								1															1	1	3
-1.99																									
	1	3	1		1		2	1	4	2	1	2	4	5	2	4	3	4	3	3	2	1			49
-0.99							2	1	1	2	1	2	3	4	1	3	1	2	1	1	1				26) 242
	10	9	10	11	9	12	9	9	10	7	9	10	7	6	12	7	11	6	8	5	8	9	10	12	216)
0.01																									
	8	7	7	8	10	7	4	8	8	8	7	6	10	7	7	10	9	12	12	11	9	10	9	7	201
1.01																									
	2	4	5	3	1	4	4	5	3	4	6	6	2	3	4	4	5	4	1	5	4	4	2	3	88
2.01																									
	5	2	3	3	3	1	5	1		3	3	1	1	2	3	2	1	2	1	3	2	1	3	4	55
3.01																									
	3	1	1	3	3	3	1	2	2	2	1	2	2	3	2				4	1	2	4	3		45
4.01																									
	1	3	1			2	2	1	1					1		1			1	2	1		2	2	21
5.01																									
		1			1	1	1	2	1	2	3	2	1				1	1			1	1		2	21
6.01																									
	1	1	3	1	1		1		1	1			1								1	1	1		14
7.01																									
				1	2																				3
8.01																									
						1																			1
9.01																									
				1																					1
10.00																									
																									744

February 1968

ΔT_2

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
												1													1
-1.99																									
			2	3	2	2	2	2	2		3	3	4	2	1	1	1								30
-0.99	1	1	1	3	1	1	1	1	1		2	1	3	4	1	3	1	1						1	28)
	9	7	8	4	7	8	8	7	9	13	16	18	17	16	18	18	19	13	8	6	7	7	8	7	258)286
0.01																									
	5	7	5	7	8	8	8	8	9	10	6	6	4	7	9	5	6	10	12	11	8	9	6	8	182
1.01																									
	6	7	7	4	4	5	5	6	2	4	1		1			2	1	3	4	5	4	4	5	3	83
2.01																									
	2	5	3	4	3	3	3	2	4		1							1	4	4	8	6	6	3	62
3.01																									
	4		1	2	3	1	2	3	1	1									1	2	1	1	3	6	32
4.01																									
	2	1	1		1	1			1	1								1		1	1	1	1	1	14
5.01																									
		1		2																		1			4
6.01																									
			1														1								2
7.01																									
8.01																									
9.01																									
10.00																									
																									696

Hour (MST)

March 1968

ΔT_2

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
-1.99																									
-0.99										1	1	1	1		1	4	2	3		1					15) 388
	11	11	12	13	13	13	11	12	15	14	14	22	26	26	24	16	15	13	22	16	15	13	14	12	373)
0.01																									
	12	12	11	11	9	7	7	8	5	7	10	7	3	3	4	6	10	10	7	11	12	14	11	16	213
1.01																									
	5	4	4	2	3	6	6	4	3	2	1						1			1	3	4	5	2	56
2.01																									
	1	1	1	2	4	4	3	1	4	2	1												1	1	26
3.01																									
	1	2					3	6	2	3															17
4.01																									
			1	1	2	1																			5
5.01																									
			1	1																					2
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									744

April 1968

ΔT_2

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99																									
-1.99																									
		2	1			1	3	4	7	6	5	6	5	6	4	3	3	3		1	1	1	1		63
-0.99							2	4	4	5	2	2	3	3	5	1	1	1		1					33)
	8	9	12	16	15	17	16	18	16	18	22	20	20	17	18	23	24	20	22	17	16	15	14	14	407) 440
0.01																									
	17	16	10	10	10	8	7	3	3	1	1	2	2	4	4	3	2	6	8	10	11	9	11	14	172
1.01																									
	5	3	6	2	3	2	2	1												1	2	5	4	2	38
2.01																									
			1	1	1	1																			4
3.01																									
				1		1																			2
4.01																									
					1																				1
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									750

May 1968

ΔT_2

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
									1	1															2
-2.99																									
							4	9	10	5	5	1			2		1								37
-1.99																									
		2	2	1	1	14	18	12	14	19	20	22	13	20	22	20	19	12	2					1	234
-0.99		1	1			1	3	1	5	2	2	5	6	7	5	2	6	5	1					1	54)258
	9	7	8	10	16	15	6	9	1	3	3	3	9	4	2	9	4	13	23	15	11	9	7	8	204)
0.01																									
	13	13	11	12	11	1					1		3				1	1	5	13	7	11	11	11	125
1.01																									
	5	2	6	4	3															3	12	10	8	8	61
2.01																									
	1	4	3	4						1											1	1	2	3	20
3.01																									
	3	2																					1	1	7
4.01																									
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									744

June 1968

$\mathcal{I}_2$

Temp. Grad. °C(100m)$^{-1}$	Hour (MST) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
								2	3	4	3	2							1						15
-2.99																									
							1	4	4	5	4	7	7	3	4	5	5		1	1					51
-1.99																									
					1	3	7	10	9	12	13	14	16	15	12	15	12	18	12	6			1		176
-0.99				1	1		2	2	4	2	5	4	4	2	5	2	3	2	1	1	1				42) 266
	9	9	7	6	8	15	16	11	9	7	5	3	2	6	6	6	9	9	13	17	18	12	11	10	224)
0.01																									
	11	12	12	10	9	6	4						1	4	2	2	1	1	2	5	11	13	10	12	128
1.01																									
	6	4	6	9	6	5			1						1							5	5	5	53
2.01																									
	2	2	3	3	4	1		1															3	3	22
3.01																									
	2	3	2	1																					8
4.01																									
				1																					1
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									720

July 1968

ΔT_2

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
								2	4	3	5	2					1	1							18
-2.99																									
							1	5	4	6	5	8	3		1	3	3	3	1						43
-1.99																									
						3	11	12	13	13	14	16	20	10	13	18	22	17	13	9					
-0.99										3	4	3	6	5	7	6	5	10	1	5					55
	5	4	3	4	7	13	14	11	9	5	3	2	1	13	8	3			16	13	11	8	6	5	164
0.01																									
	15	10	12	8	7	9	4	1		1			1	2	1	1				4	19	13	14	17	139
1.01																									
	5	11	8	15	9	5	1		1					1	1						1	7	10	5	80
2.01																									
	4	4	5	2	7																	3	1	3	29
3.01																									
	2	2	3	2	1	1																		1	12
4.01																									
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																									744

APPENDIX IV b

Frequency distributions of vertical temperature gradients between 3 m. and 61 m. and 3 m. and 31 m. on the Calgary Tower in southeastern Calgary. All temperature differences are converted to a standard height interval of 100 m.

Note that the typed numbers are frequencies for 1°C temperature-gradient intervals. The frequencies listed for -0.99°C$(100m)^{-1}$, which indicate the dry adiabatic lapse rate, have to be added to the row below to give the frequencies in the temperature interval -0.99 to 0.01.

March 1968

ΔT_1

Hour (MST)

Temp. Grad. $^{\circ}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
													1									1		1	3
-9.99																									
-8.99																									
-7.99																									
-6.99																									
													1												1
-5.99																									
														1											1
-4.99																									
												1	2	1	1	1									6
-3.99																									
										1	2	2	3	1	1					1	1				12
-2.99																									
						1		1	3	7	10	11	7	7	7	2	1					1			58
-1.99																									
	2	2		1		2	4	8	8	12	9	6	7	9	9	15	8	2	2	1	2	1	2	2	114
-0.99	1	1		1		1	2	2		2	1	2	1			2	2		1		1	1	1	2	24) 155
	5	5	8	7	9	4	5	7	12	1	1			4	5	3	10	10	8	10	8	7	7	3	139)
0.01																									
	3	2	1	1	2	1	2	3				1	1				2	5	3	4	2	3	1	2	39
1.01																									
	2	2	2		4	6	2	1										2	4		1	2	3	2	33
2.01																									
	3	2	2	5	1		2	1										2	1	2	1	1	3	2	28
3.01																									
	2	3	3	2	2	3	3											2	1	1	1	1	2	3	29
4.01																									
	1	1	1	1		1													1		2	1		1	10
5.01																									
	2		2	1			1													1	1			1	9
6.01																									
		2		1																1	1	1			6
7.01																									
				1																	1		1		3
8.01																									
	1		1	1	2	1	2												1	1	1	2	3	1	17
9.01																									
						2																		2	4
10.00	1	3	3	1	3	1													1	1		1		1	16
																									552

March 1968

ΔT_4

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
													1											1	2
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
														1											1
-2.99																									
								1	1		4	5	7	4	5	3		1							31
-1.99																									
	2	3	1	2	3	2	2	9	12	21	19	17	15	17	13	17	10	1	1	2	1		1	2	173
-0.99	1		1	1		2	1	1	1	2		1			1		1	1		1	1	2	1	1	20) 156
	5	5	6	6	6	4	8	7	8						4	3	11	12	10	9	11	7	8	6	136)
0.01																									
	3	3	1	1	2	4	2	2	1					1			1	2	4	3	2	7	2	1	42
1.01																									
	4	2	4	4	4	2	4											4	4	2	2	1	5	2	44
2.01																									
	2	4	3	1	3	4	3	3										1	1	1	2	1	2	4	35
3.01																									
	3	1	2	4	1	1	1											1	1	2	2	1		1	21
4.01																									
	2			2	1	1	1														1	2	1		11
5.01																									
		1	1		2														1	1	1		2	2	11
6.01																									
		1	2	1		2														1		2	1	1	11
7.01																									
		2	2	1	1		1												1	1				2	11
8.01																									
						1																			1
9.01																									
	1																								1
10.00																									
		1																							1
																									552

April 1968

ΔT_1

Hour (MST)

Temp. Grad. °C(100m)$^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
														1											1
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
											1			1											2
-4.99																									
								1		1	1	3	1	1											8
-3.99																									
									2	6	3	7	8	5	6										37
-2.99																									
								2	9	10	11	13	11	10	12	6	3								87
-1.99																									
	2	1			1	3	8	12	7	8	8	2	5	8	6	17	15	6						1	110
-0.99		1			1	2	2	3	2	1	1		1	1		2	3	2							22) 208
	8	9	11	10	9	6	10	7	8	2	3	4	3	2	4	4	8	18	18	11	8	8	7	8	186)
0.01																									
	1	4	2	1		4	2	2			1				1				1	5	5	4	4	5	42
1.01																									
	2	1	1	2	2	2	2		1	1								2	3	5	4	3	5	1	37
2.01																									
	4	1	2	2	3	4	1	1											2	1	5	5	1	2	34
3.01																									
		4		2	1	3	2												1	2		3	3	1	22
4.01																									
	3	2	3	3	5	2												1	1	1	2		4	1	28
5.01																									
	2	2	3	1	1		1												1	2	3	2	1	3	22
6.01																									
		1	2		2	2	1	1											1		1	1	3	2	17
7.01																									
	2	1	1		1																				5
8.01																									
	4	2		3	1														1	1		1		3	16
9.01																									
			1	2																1		1			5
10.00																									
		1	3	3	2	1															1	1	1	2	15
																									696

April 1968

ΔT_4

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
													1												1
-9.99																									
-8.99																									
-7.99																									
									1																1
-6.99																									
-5.99																									
-4.99																									
-3.99																									
											1	2	1												4
-2.99																									
								1	2	9	9	11	13	13	11	1									70
-1.99																									
							1	14	17	16	16	13	10	13	14	22	20	7							163
-0.99			1			2	5	4	3					1	1	1	2	4							24)219
	10	12	11	10	10	10	11	6	5	3	2	3	4.	2	2	5	6	15	19	13	9	9	7	11	195)
0.01																									
	6	2	1	3	2	3	4	1	1	1	1				1		1	1	5	9	8	6	9	4	69
1.01																									
	1		2	3	4	5	1	2										1	1	1	4	5	1	2	34
2.01																									
	1	6	4	2	2	3	2												2	1	2	4	4	2	35
3.01																									
	1	2	2	1	4	2	2	1											1	2	4		1	1	24
4.01																									
	2	1	1	3	3	2	1											1	1	2		1	3	4	25
5.01																									
	4	2		1		1															1	2	1	2	14
6.01																									
	4		5	2	2																	2	2	2	19
7.01																									
		3		2																1				1	7
8.01																									
			1	2	1																		1		5
9.01																									
					1	1															1				3
10.00																									
		1	1																						2
																									696

May 1968

ΔT_1

Hour (MST)

Temp. Grad. $^oC(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
																1									1
-9.99																									
-8.99																									
																1									1
-7.99																									
-6.99																									
										2	2	3	1	3											11
-5.99																									
										2	3	2	4		2										13
-4.99																									
	1	1					1		3	4	5	6	6	2	2	1									32
-3.99																									
				1		1		2	6	4	5	4	6	7	4	11	2						1	1	54
-2.99																									
	2		1		1	1	5	11	12	15	10	12	6	11	10	5	9	3				1			
-1.99																									
		1	2	1	2	6	19	15	9	3	5	4	8	8	9	8	10	16	4	2			1	1	134
-0.99			1		1	4	2	1							2	1	2	9	2						25) 167
	8	9	7	9	7	16	4	2	1	1	1				2	2	7	2	14	13	12	10	7	8	142)
0.01																									
	2	4	3	6	9											1		1	7	3	2	4	5	6	53
1.01																									
	2	5	2	3	1	2													2	6	7	2	4	2	38
2.01																									
	3	1	2	1	4												1		1	3	1	5	3	5	30
3.01																									
	3	3	5	4	3	1														1	4	1	3	1	29
4.01																									
	3		4	2	2															2	1	3	2		19
5.01																									
	2	3	1	2																1	2	3	1	5	20
6.01																									
	2	1	1	1																	1	1	1	2	10
7.01																									
	1		1																		1		2		5
8.01																									
		1		1																					2
9.01																									
	2	1	1		1																				5
10.00																									
		1																				1	1		3
																									744

May 1968
ΔT_4
Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
											1	3	1												5
-3.99																									
									1	5	7	6	8	6	2	1									36
-2.99																									
						1		5	10	14	13	10	12	12	13	13	7								110
-1.99																									
	3	2	2	2	2	4	22	24	18	12	10	12	10	13	12	15	18	19	5	2		1	1	3	212
-0.99		1			1	4	3	2	2						2		1	3							19) 193
	11	8	11	10	10	20	6								2	2	5	9	19	16	13	13	9	10	174)
0.01																									
	2	9	3	6	7														6	5	4	2	8	4	56
1.01																									
	5	2	3	3	5	2													1	4	5	4	4	5	43
2.01																									
	2	1	4	3	3															3	6	5	3	2	32
3.01																									
	1	3	3	3	1																1	3	1	4	20
4.01																									
	4		3	1																	1	2	4	2	17
5.01																									
	1	2		1	1																			1	6
6.01																									
	2	3	1		1																1	1			9
7.01																									
			1	1																					2
8.01																									
																				1			1		2
9.01																									
				1																					1
10.00																									744

June 1968

ΔT_1

Temp. Grad. $^oC(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
													1												1
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
										1	1		1					1							4
-4.99																									
									1	2	2	3	5	1	2	1									17
-3.99																									
								1	4	7	8	11	6	6	1	3	1								48
-2.99																									
						1	3	8	10	13	10	10	11	11	11	8	5	2							103
-1.99																									
					2	3	13	13	9	2	5	3	3	7	10	9	13	8	2		1		1	1	105
-0.99					1	2	5	2	2		2	1		1	2	1	3	1	2		1		1		27)180
	6	6	6	7	4	17	5	4	2	3			1	2	1	6	6	15	15	14	9	11	8	5	153)
0.01																									
	1	2	4	2	8	1												1	4	2	5	3	4	4	41
1.01																									
	5	4	2	4	4	2													4	5	4	5	2	3	44
2.01																									
	7	4	4	5	4										1				1	5	2	4	6	8	51
3.01																									
	2	3	3	2	2		1													1		2	3	1	20
4.01																									
	1	2	4	4			1													1	2		1	1	17
5.01																									
	1	3	3		1																3	1			12
6.01																									
	2	2	1	2																				4	11
7.01																									
				2	1																1	1			5
8.01																									
	1	1				1																		1	4
9.01																									
						1																			1
10.00																									
	2	1	1		1																	1	1	1	8
																									672

Hour (MST)

June 1968

ΔT_4

Hour (MST)

Temp. Grad. $^{o}C(100m)^{-1}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
											1														1
-3.99																									
										1	1		1												3
-2.99																									
							1	2	7	12	10	17	15	11	6	6	4	2							93
-1.99																									
				1	1	4	11	19	16	11	15	11	11	15	19	17	16	10		1					·178
-0.99						1	4	3		3								1	3	1				1	17) 195
	6	6	7	7	8	19	10	4	5	1	1		1	2	2	5	8	15	17	13	11	11	10	9	178)
0.01																									
	5	7	5	4	10														5	7	10	10	6	2	71
1.01																									
	8	4	3	6	5	2	1								1				2	6	1	3	2	8	52
2.01																									
	3	3	8	6	2		1														4	1	1	4	33
3.01																									
	3	5	4	1																	1		1	1	16
4.01																									
		1		1	1	1													1			1	2	2	10
5.01																									
	3			2		1															1	2	2		11
6.01																									
		1	1		1																		2		5
7.01																									
		1																					2	1	4
8.01																									
9.01																									
10.00																									
																									672